Observation of a Higgs Boson at the Large Hadron Collider

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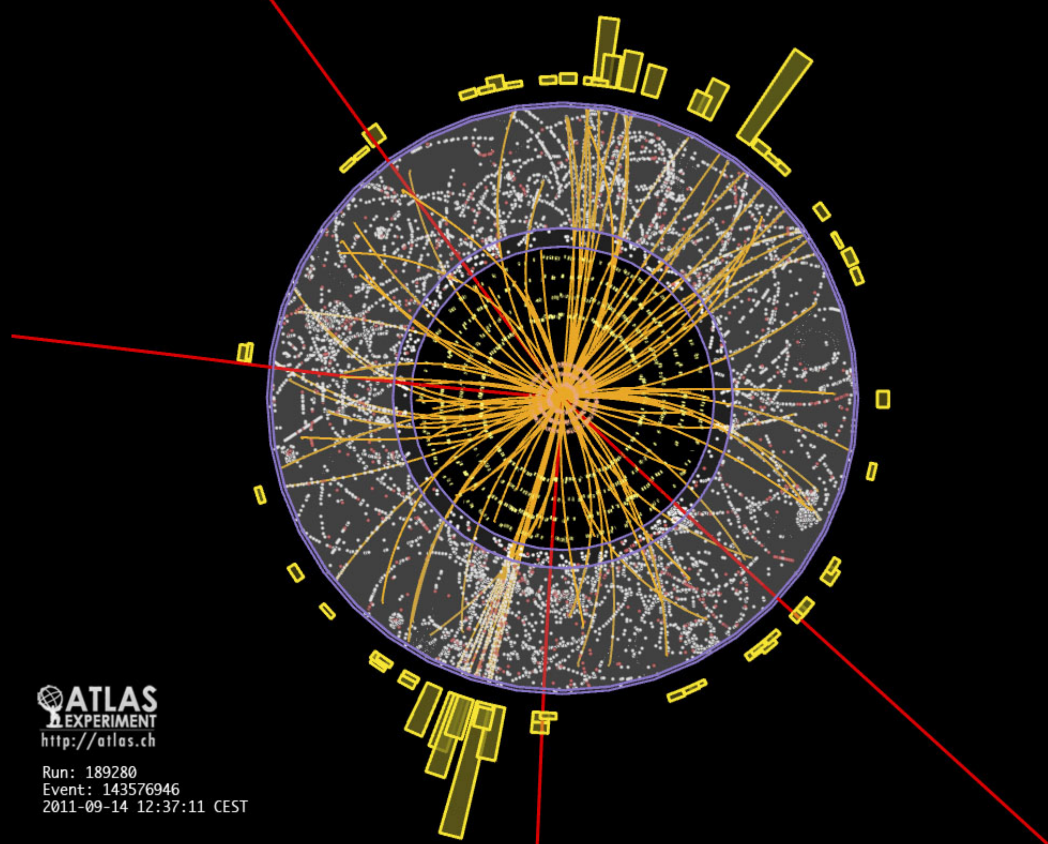


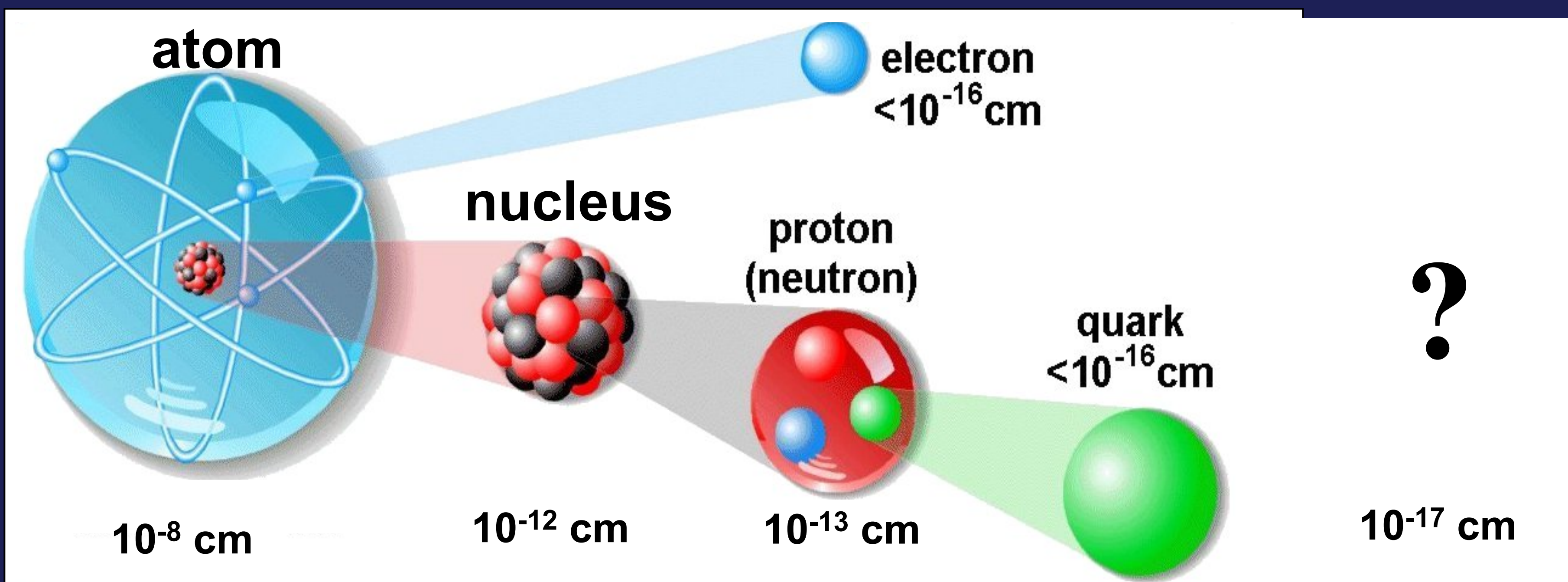
Peralta Engineering, Medicine and Science Club, May 2013

Outline

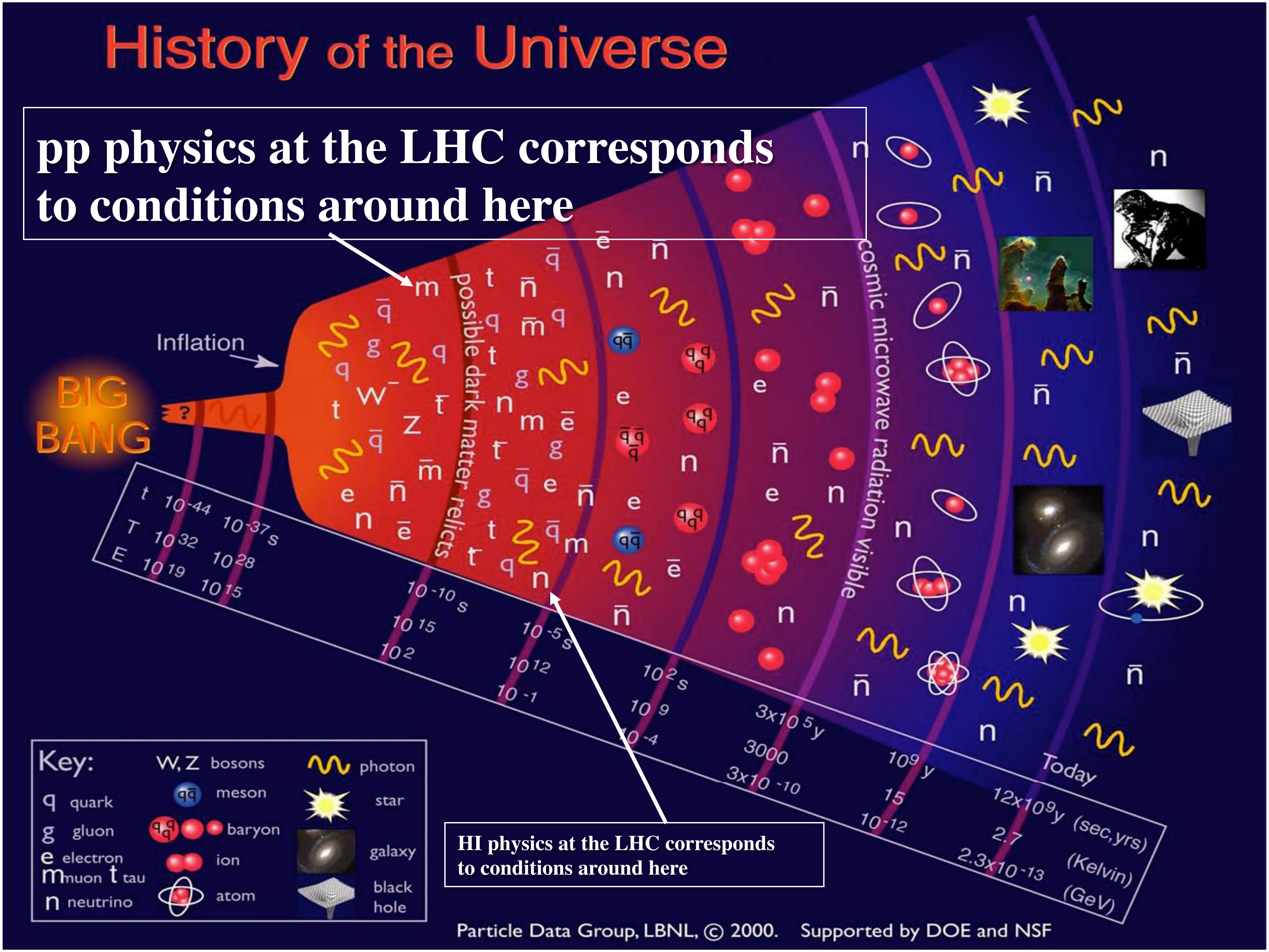
- Particle Physics and the role of the Higgs Boson
- The LHC and the ATLAS and CMS Detectors
- The Search for the Higgs Boson
- Conclusions and Outlook

In Search for Fundamental Particles

~0 | ~1910 | ~1940 | ~1970 | LHC 2010-2012



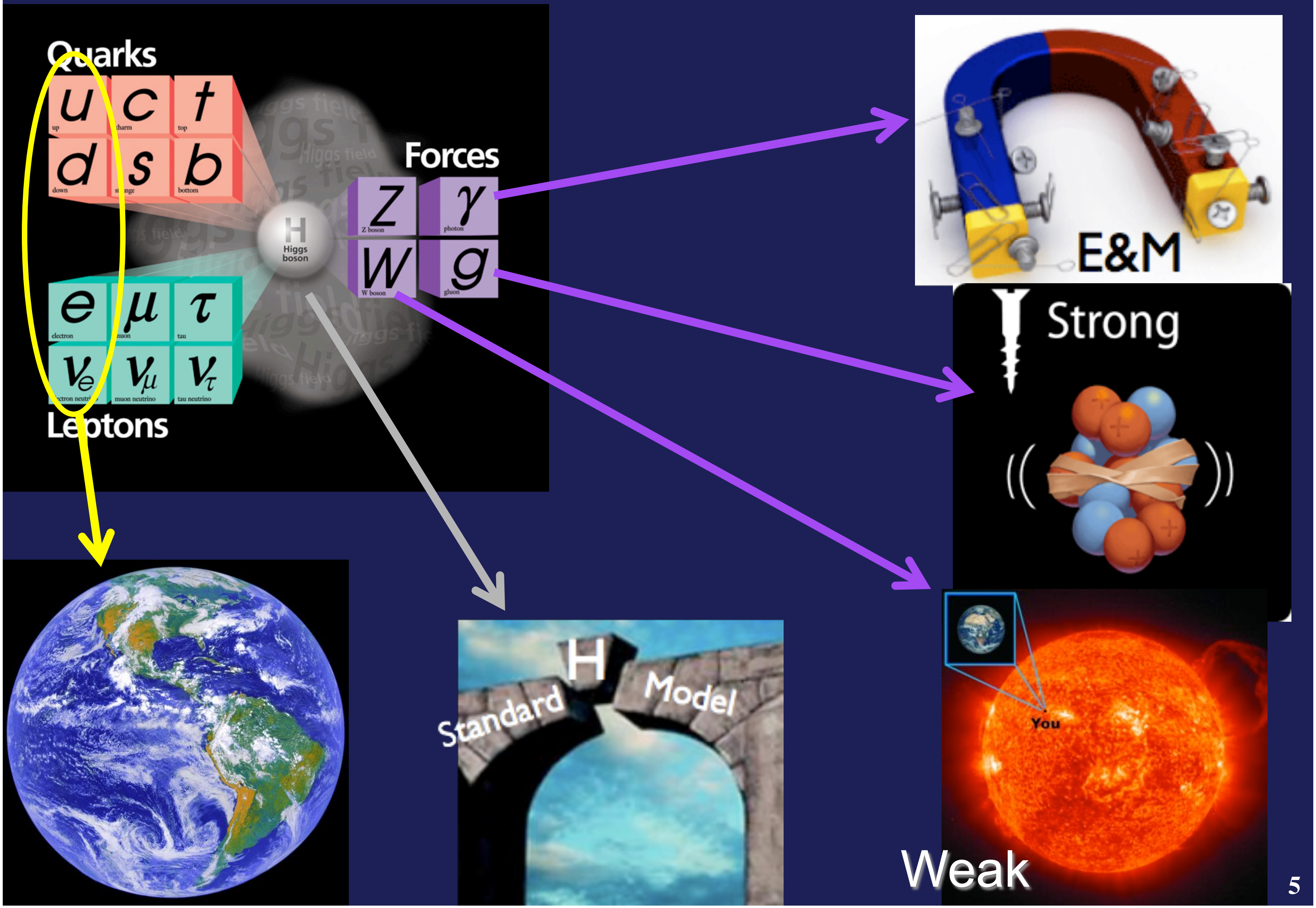
$\frac{1}{10{,}000}$ $\frac{1}{10}$ $\frac{1}{100{,}000}$ $\frac{1}{10}$



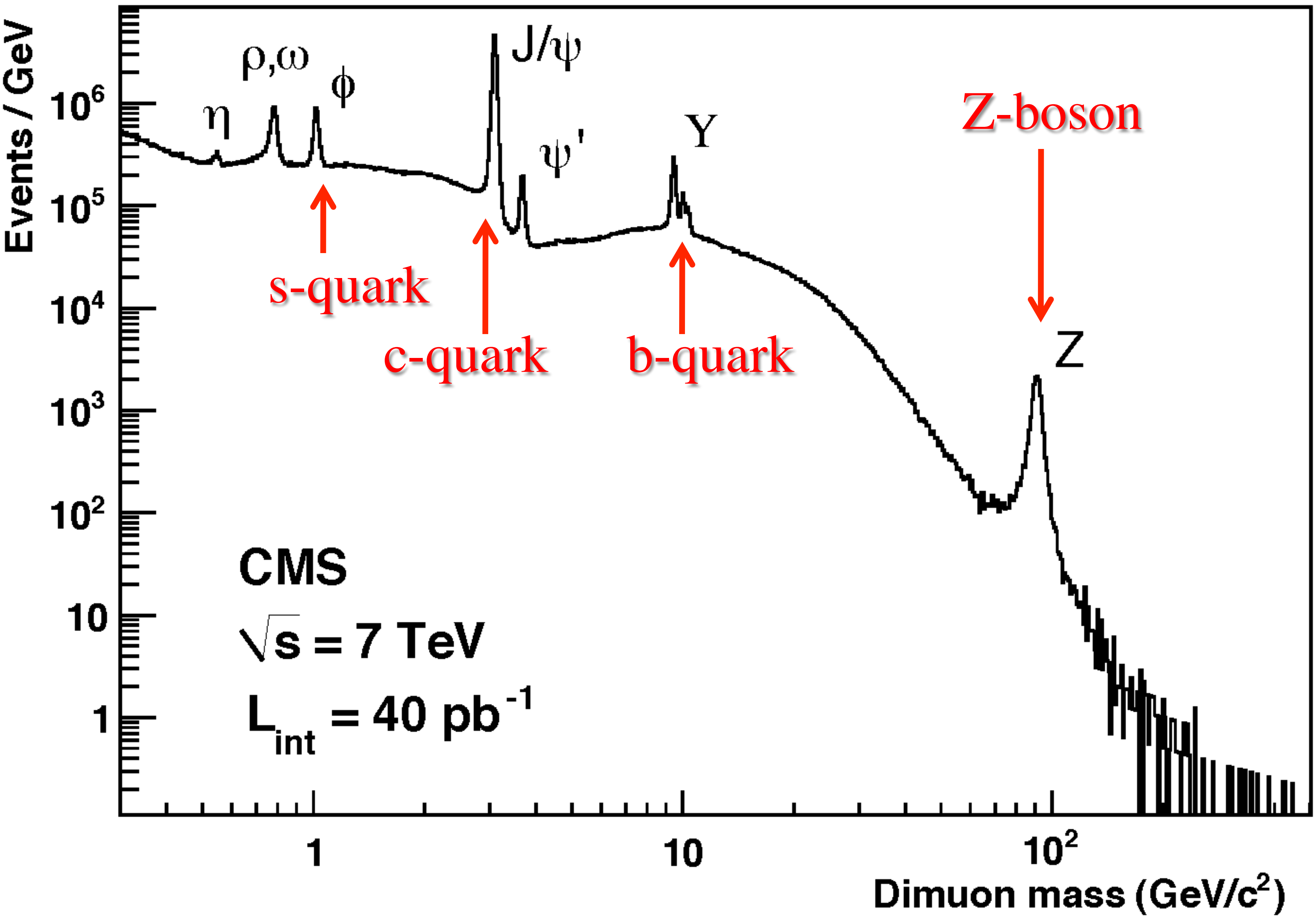
pp physics at the LHC corresponds to conditions around here

HI physics at the LHC corresponds to conditions around here

What do We Know?

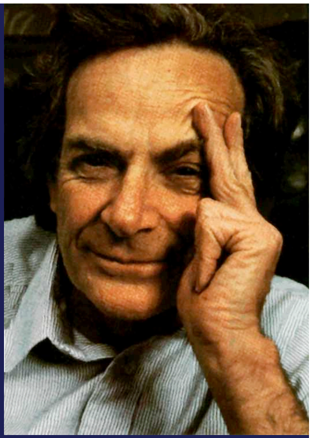


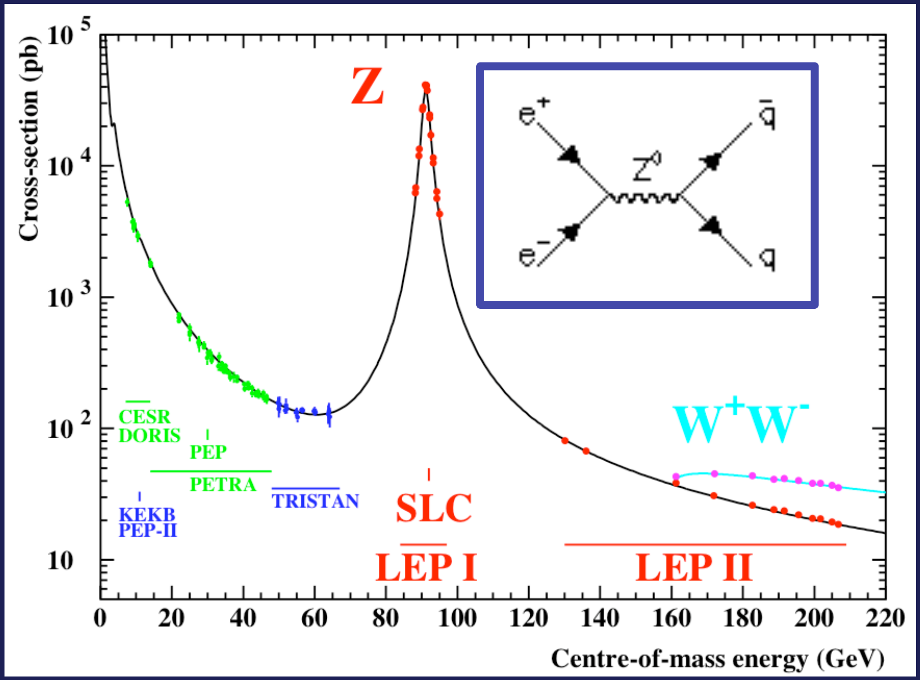
Dimuon Mass Spectrum

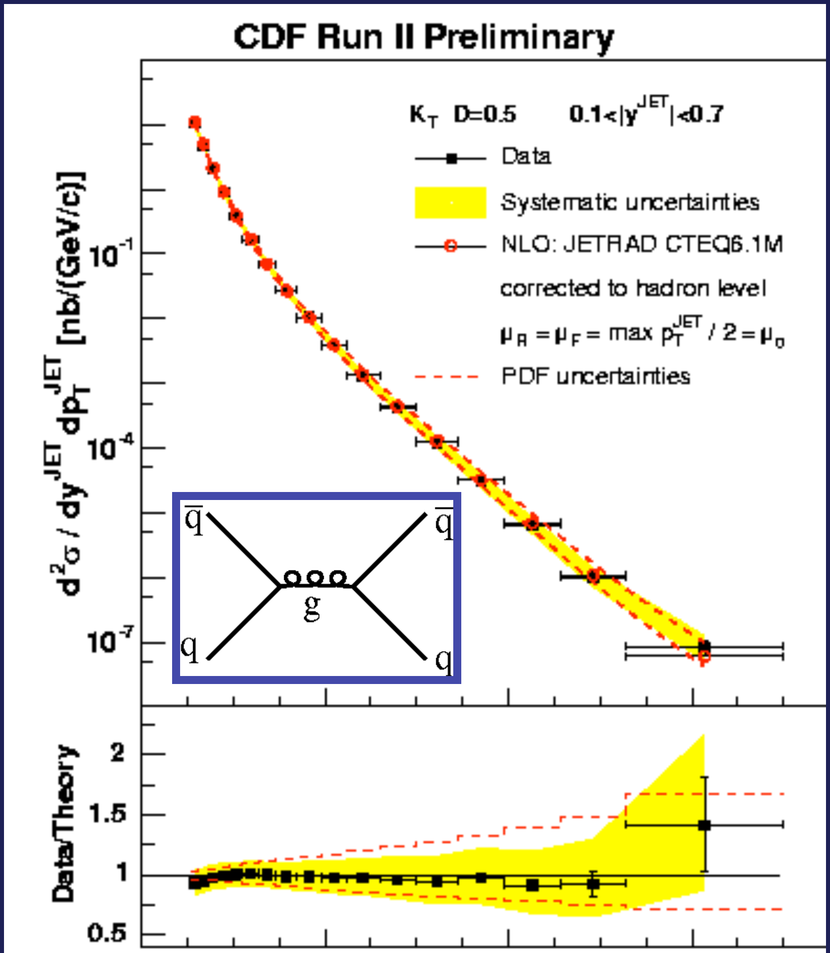


The "Standard Model": the most precise theory there is!

- "Feynman diagrams" allow us to calculate any processes with precision better than 1-10%







Tested in many experiments since 1960s

The Standard Model Formula

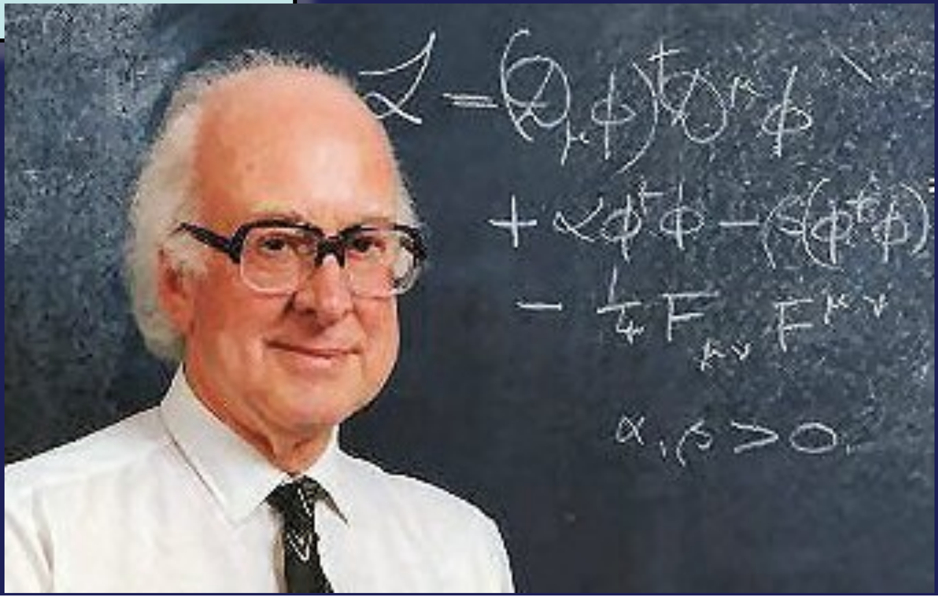
$$\begin{aligned}\mathcal{L} \;=\; & -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\,\bar{\psi}D\psi \\ & + \psi_i\lambda_{ij}\psi_j h + \text{h.c.} \\ & + |D_\mu h|^2 - V(h) \\ & + \frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j\end{aligned}$$

gauge sector

flavour sector

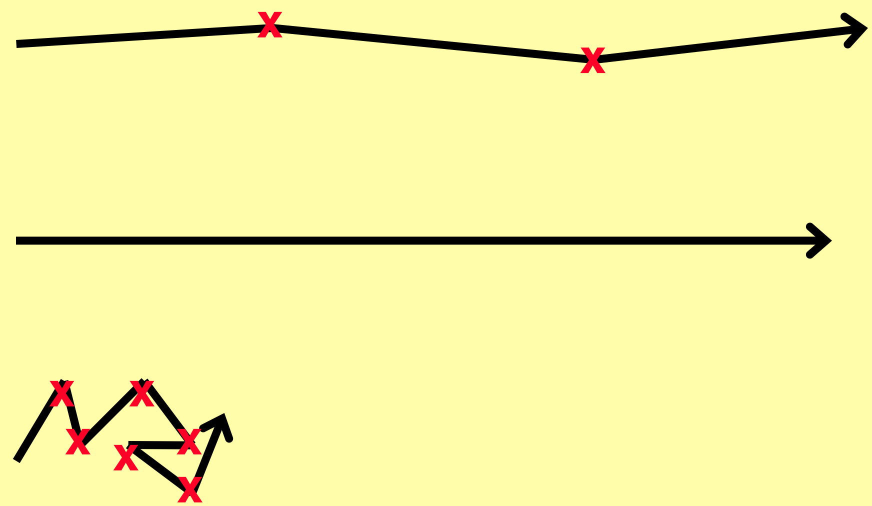
Higgs sector

ν mass sector



Why Do Particles Have Mass?

Nothing in the universe	Higgs field in the universe
Electron m=0.511 MeV/c^2	
Photon m=0	
Top Quark M~172000 MeV/c^2	



- Higgs field
  - is present everywhere
  - slows heavy particles down ⇔ gives them mass

How the Higgs Field gives Mass

Cocktail party:
Guests are evenly spread

Arrival of celebrity:
Guests cluster near celebrity

D. Miller / UCL

Celebrity moves more slowly <=> acquires mass (guests act like Higgs field)

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

… a lot happened …

by the mid 90's the Higgs boson was considered the most critical particle to be found experimentally

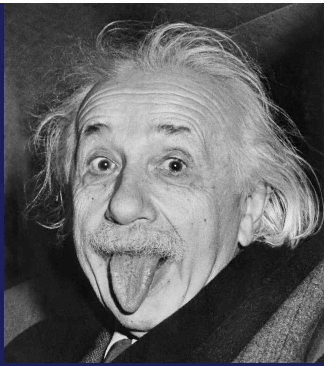
LHC and the ATLAS and CMS Detectors

Units and Numbers

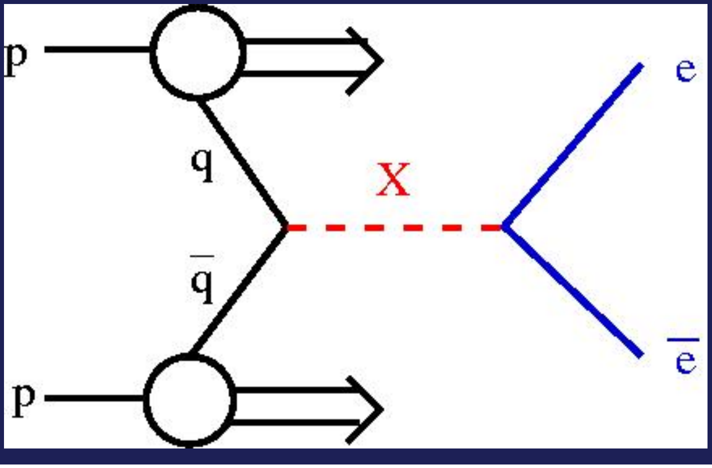
- Energy is measured in electron volts (eV):
  - *the amount of kinetic energy gained by a single unbound electron when it accelerates through an electrostatic potential difference of one volt.*
- *For example:*
  - *1 eV = $1.60217653(14) \times 10^{-19}$ joules*
  - *electron mass = $.511 \times 10^{6}$ eV/c^2*
  - *proton mass ≈ 10^9 eV/c^2 = 1 GeV/c^2 (“Giga electron volt”)*
  - *Z boson mass = 91 GeV/c^2*
  - *top quark mass=172 GeV/c^2 (≈mass of gold atom)*

TeV = “Tera electron volt”
= 10^{12} eV ≈ 1000 x proton mass / c^2

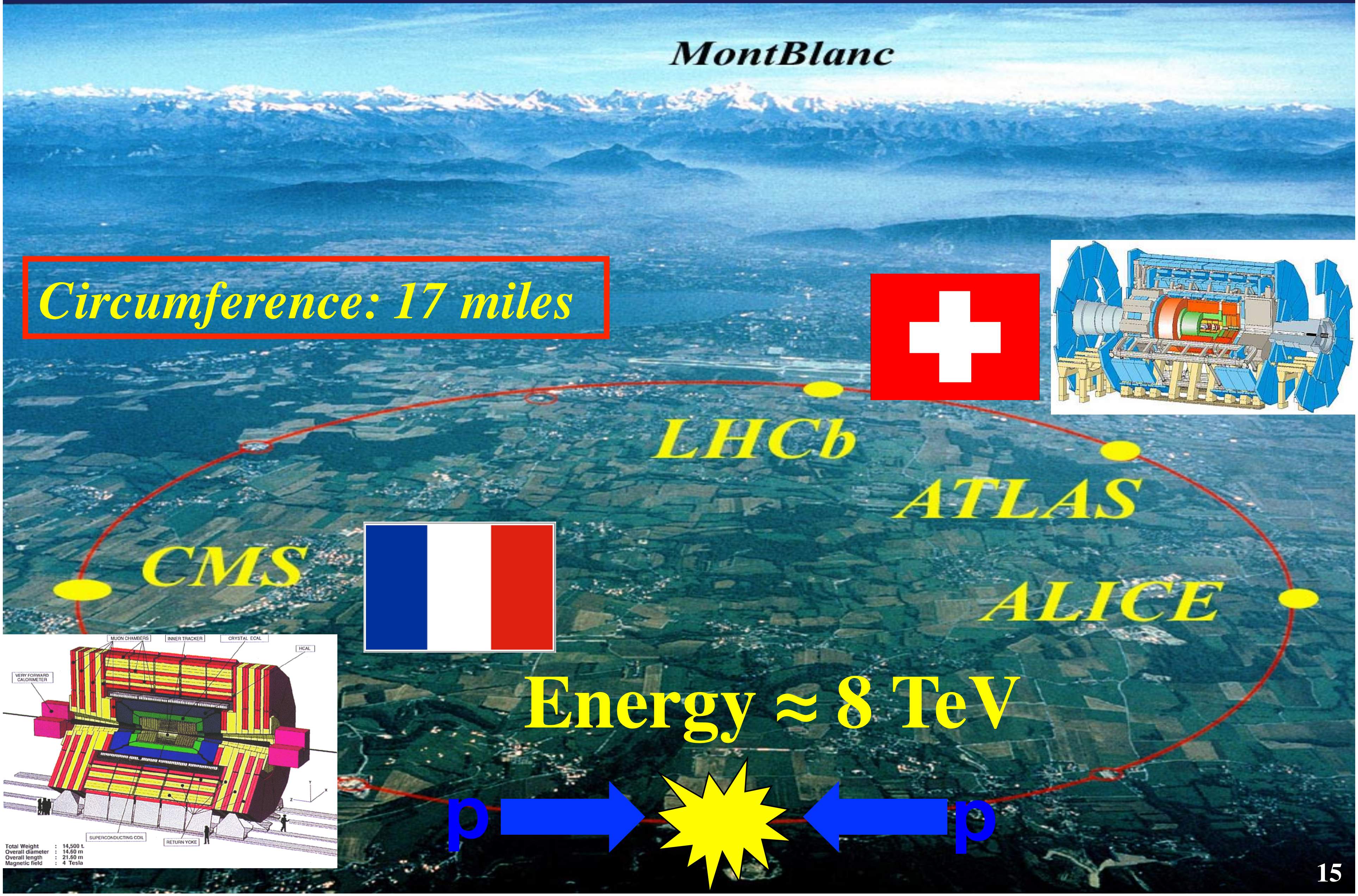
General Concept: $E=mc^2$



- Energy and mass are equivalent
  - $E=mc^2$
    - c = speed of light, m = particle mass, E = particle energy
- Collide 2 protons with E=4 TeV each
  - Total energy: 8 TeV
  - Can create particle X with mass **$m_X < 8$ TeV × c^2**
    - Actual interactions occur between quarks and gluons that carry part of proton energy
    - Most particles we create live only for a very short fraction of a second and then decay



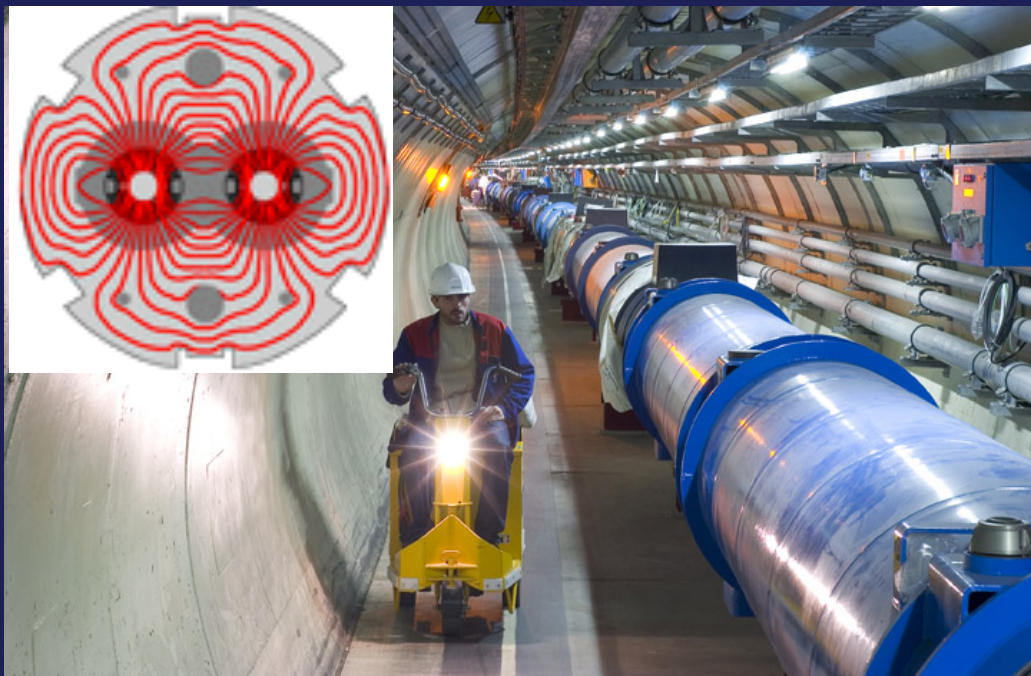
The Large Hadron Collider (LHC)



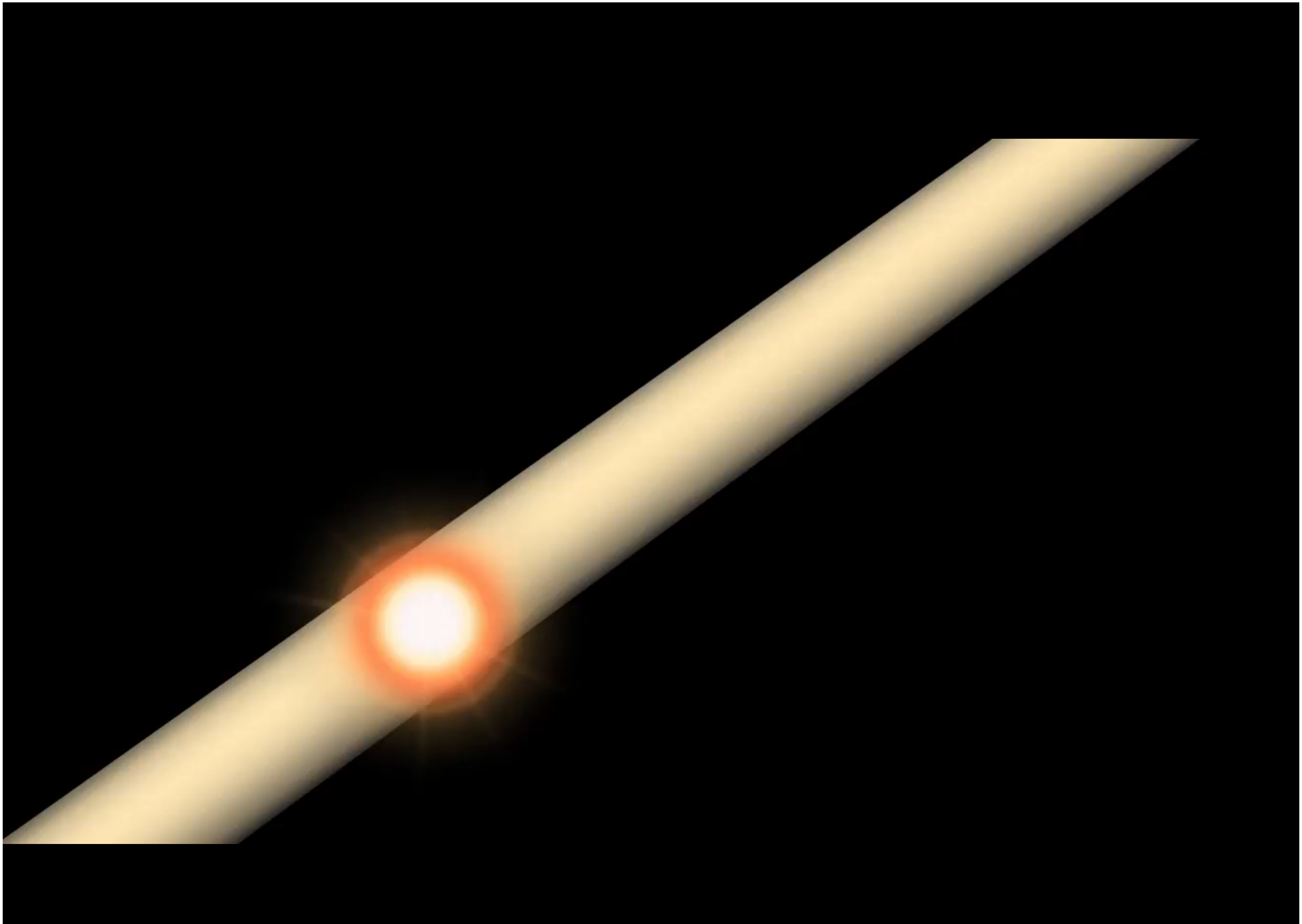
LHC in the Bay

- protons go really fast: 99.999999% of the speed of light
- make a full turn 11254 times per second

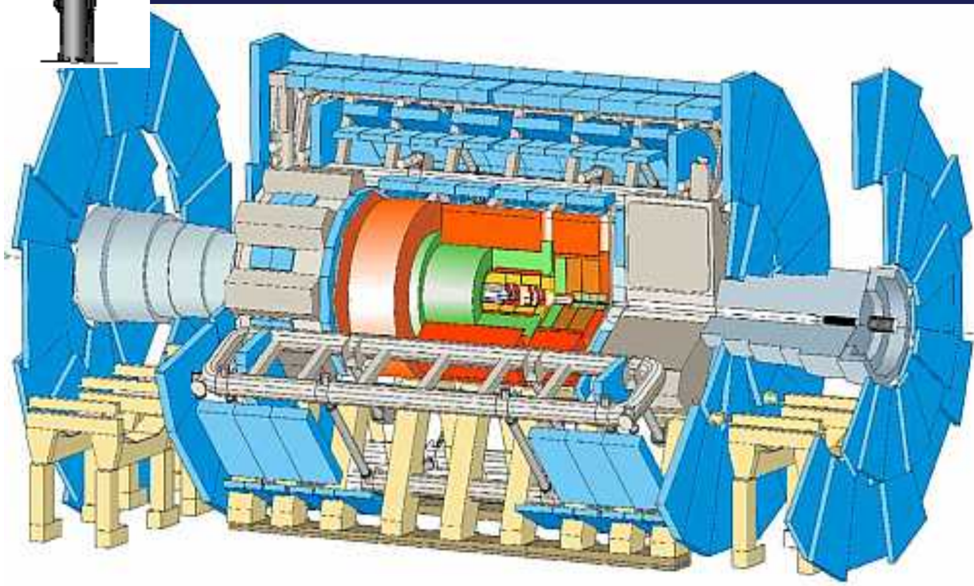
LHC Accelerator

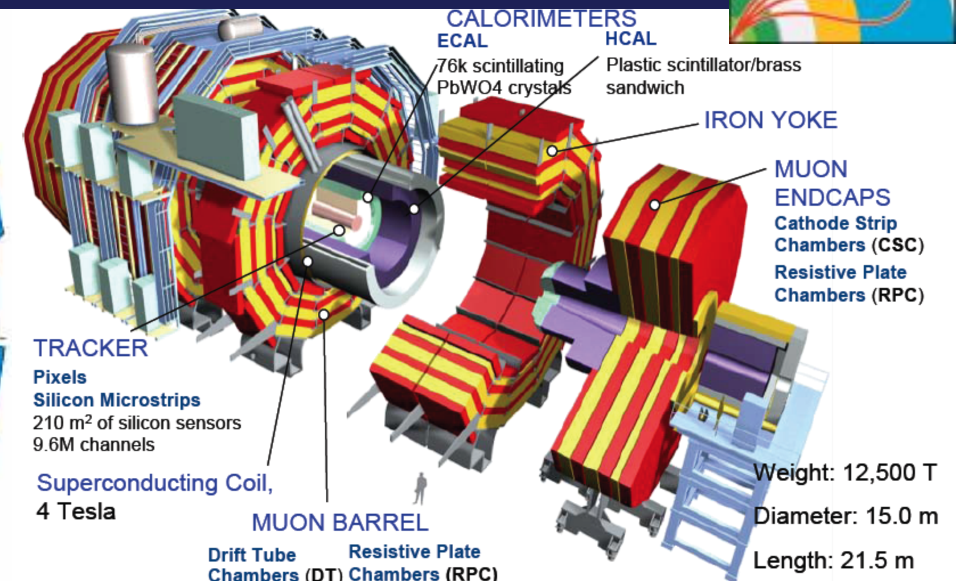


- About 300 ft under ground
- 9,600 superconducting magnets cooled to 1.9K (≈ -271 C)
- Dipole magnets operate at a field of up to 8 Tesla



ATLAS and CMS Detectors





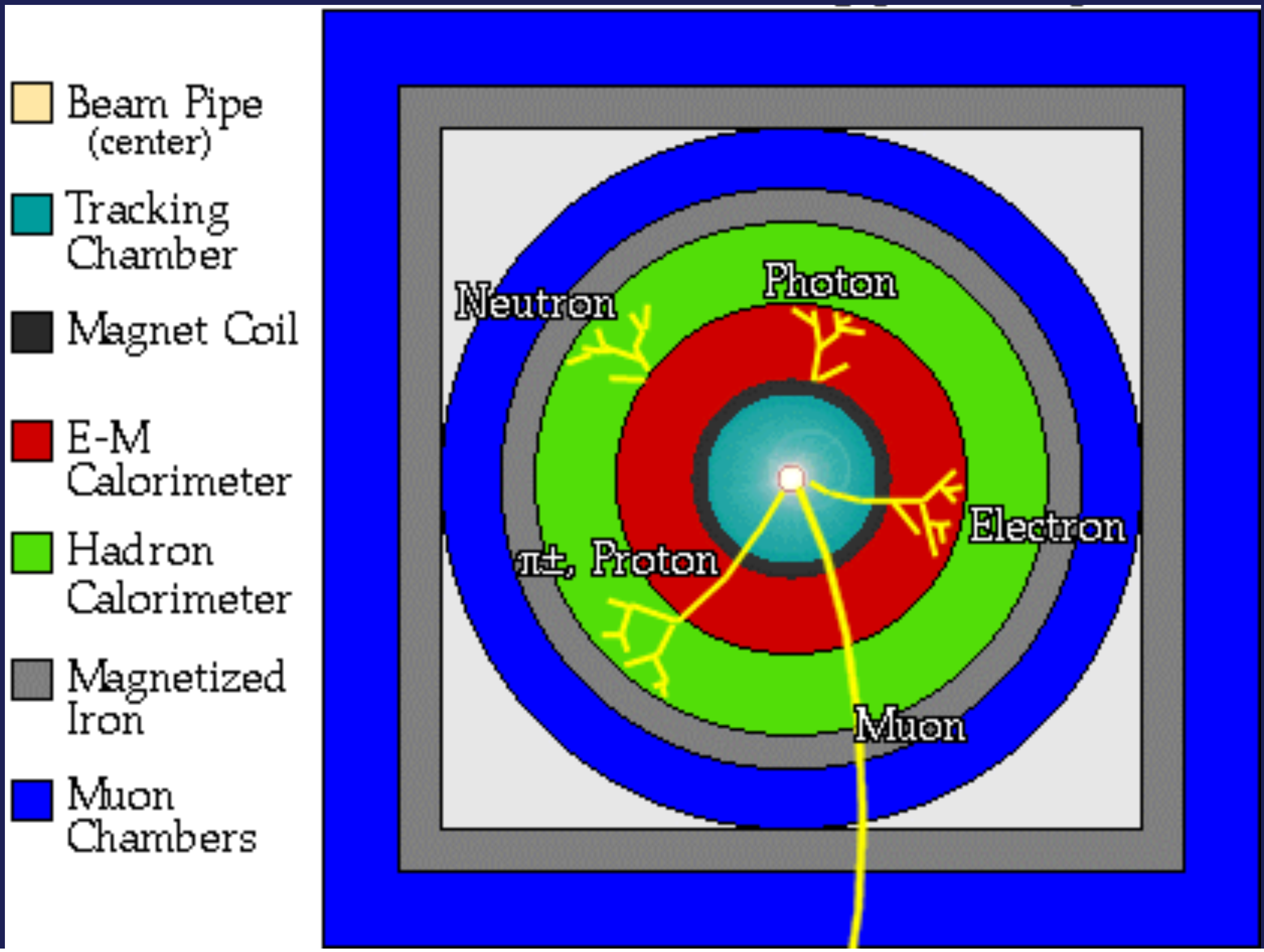
	Weight (tons)	Length (ft)	Height (ft)
ATLAS	7,000	140	80
CMS	12,500	70	50

Detector Mass in Perspective

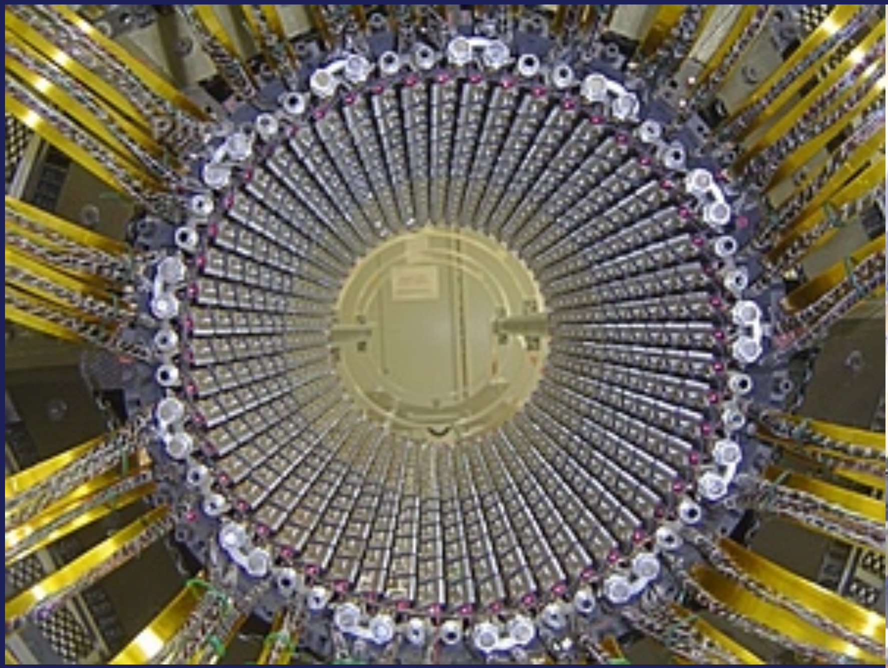
CMS is 30% heavier than the Eiffel tower

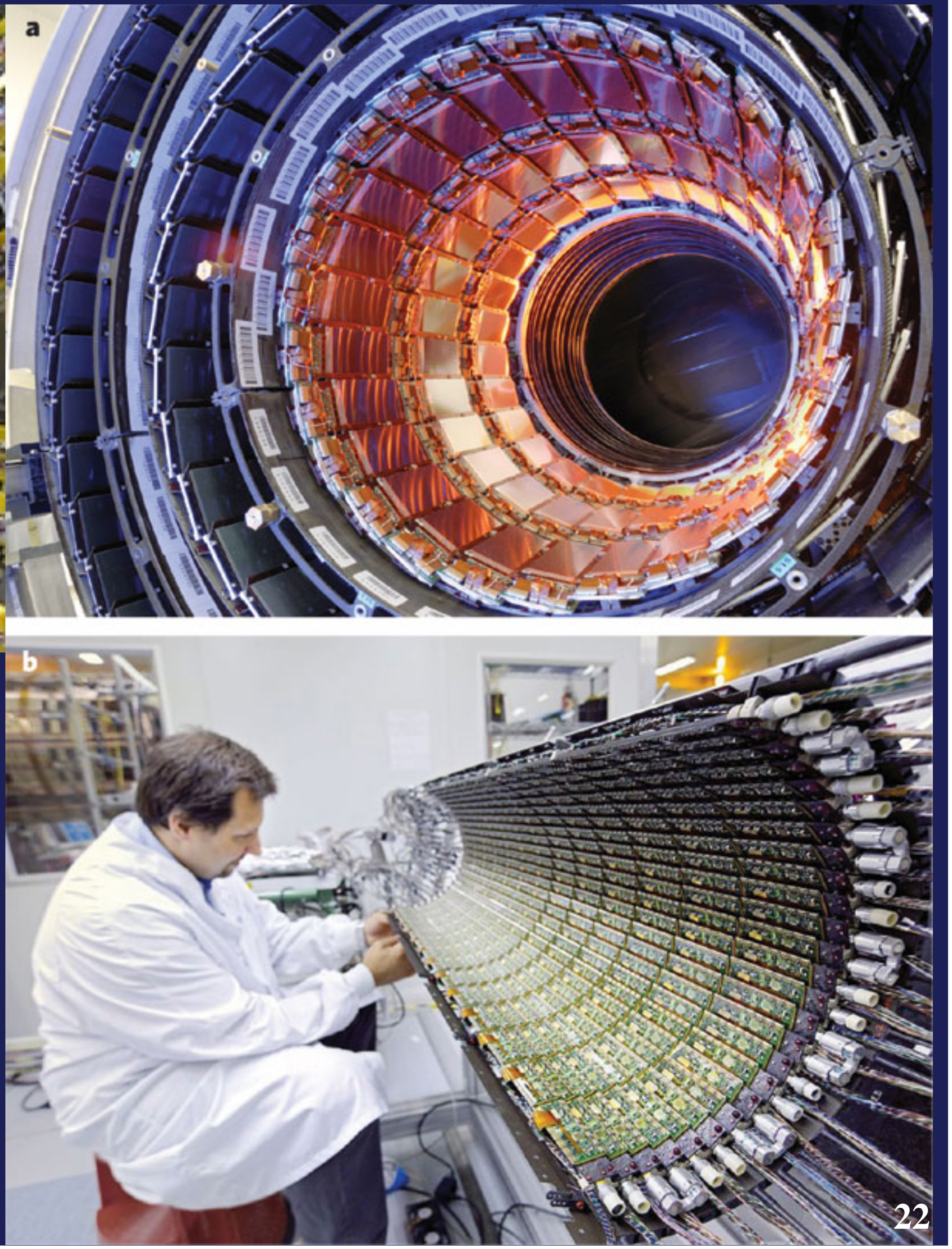
Particle Identification

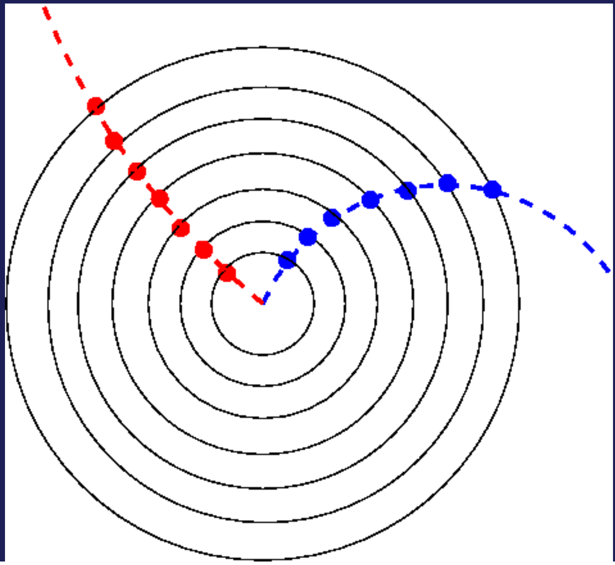
- Collisions enclosed by layers of different detectors:
  - separate particle types
  - measure their energies and angles



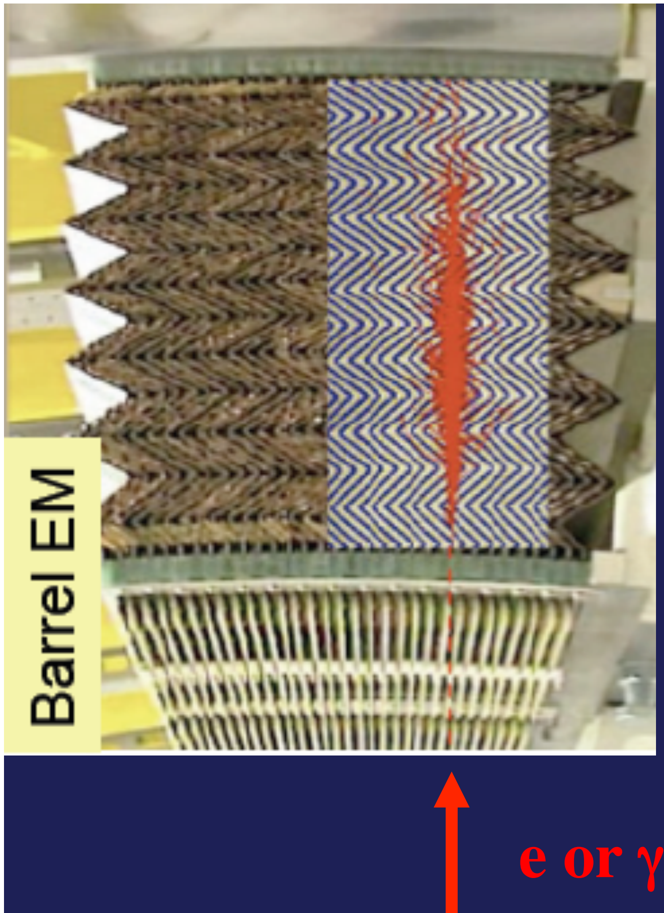
Tracking Detectors

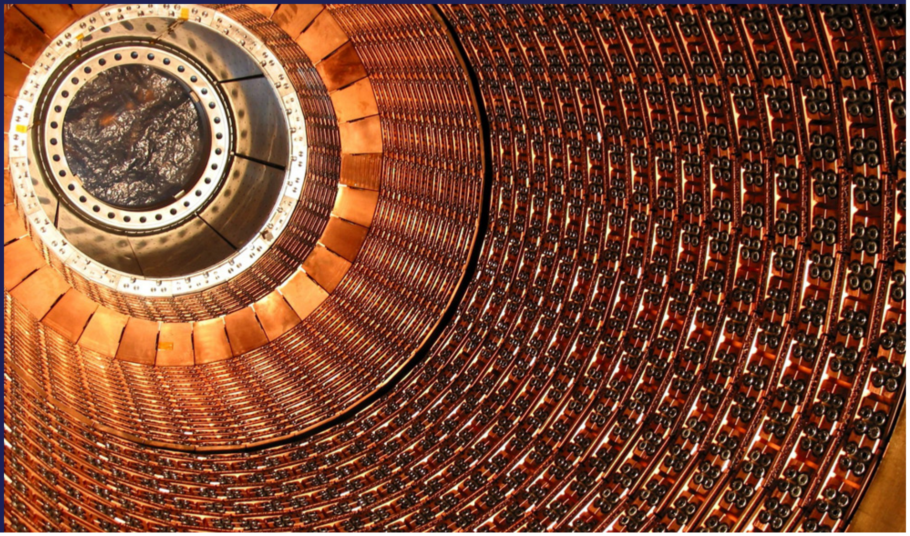




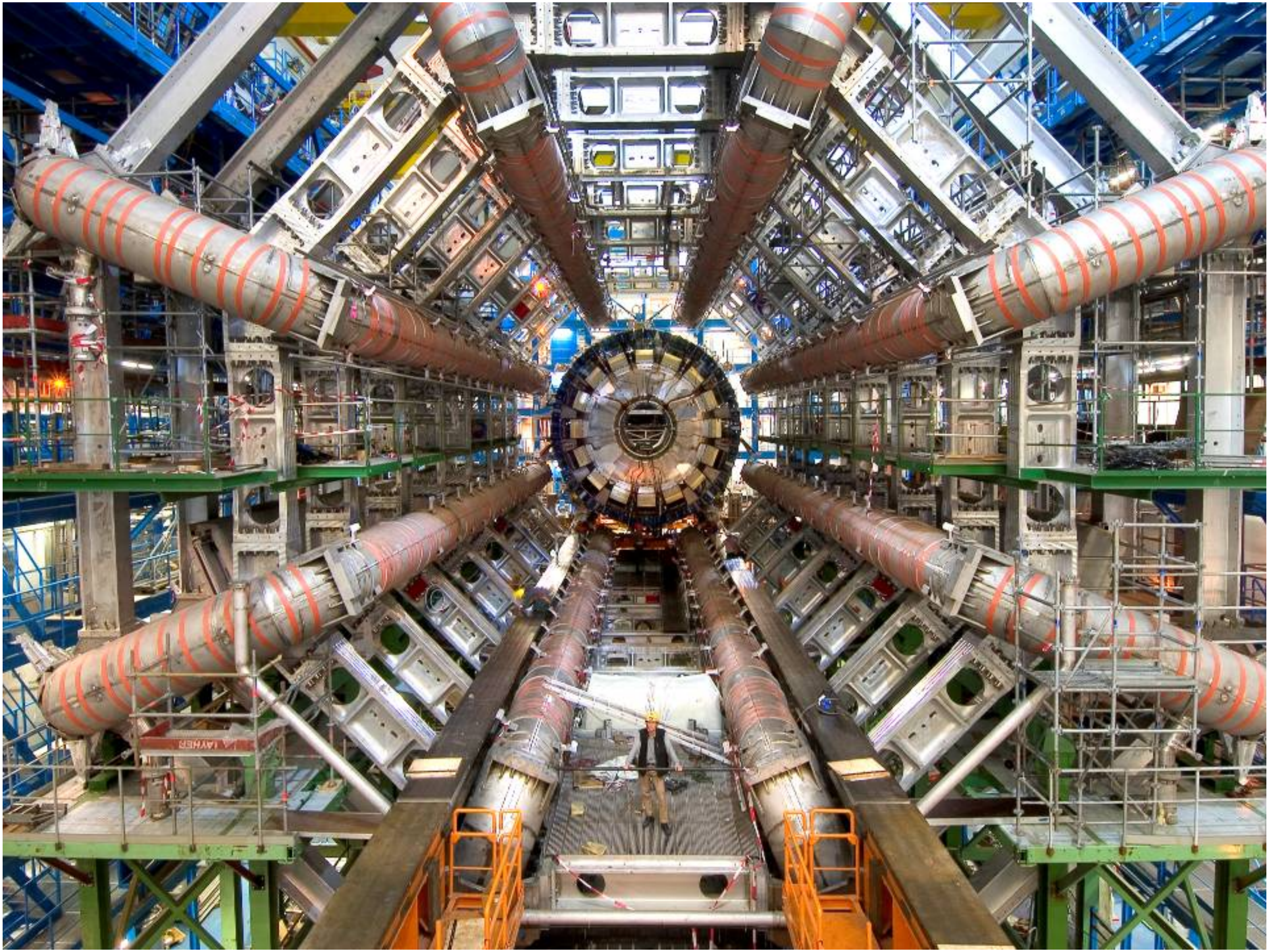


Calorimeters





- Measure energy and position of electrically charged and neutral particles
  - Electrons and photons
  - Hadrons (protons, pions,…)



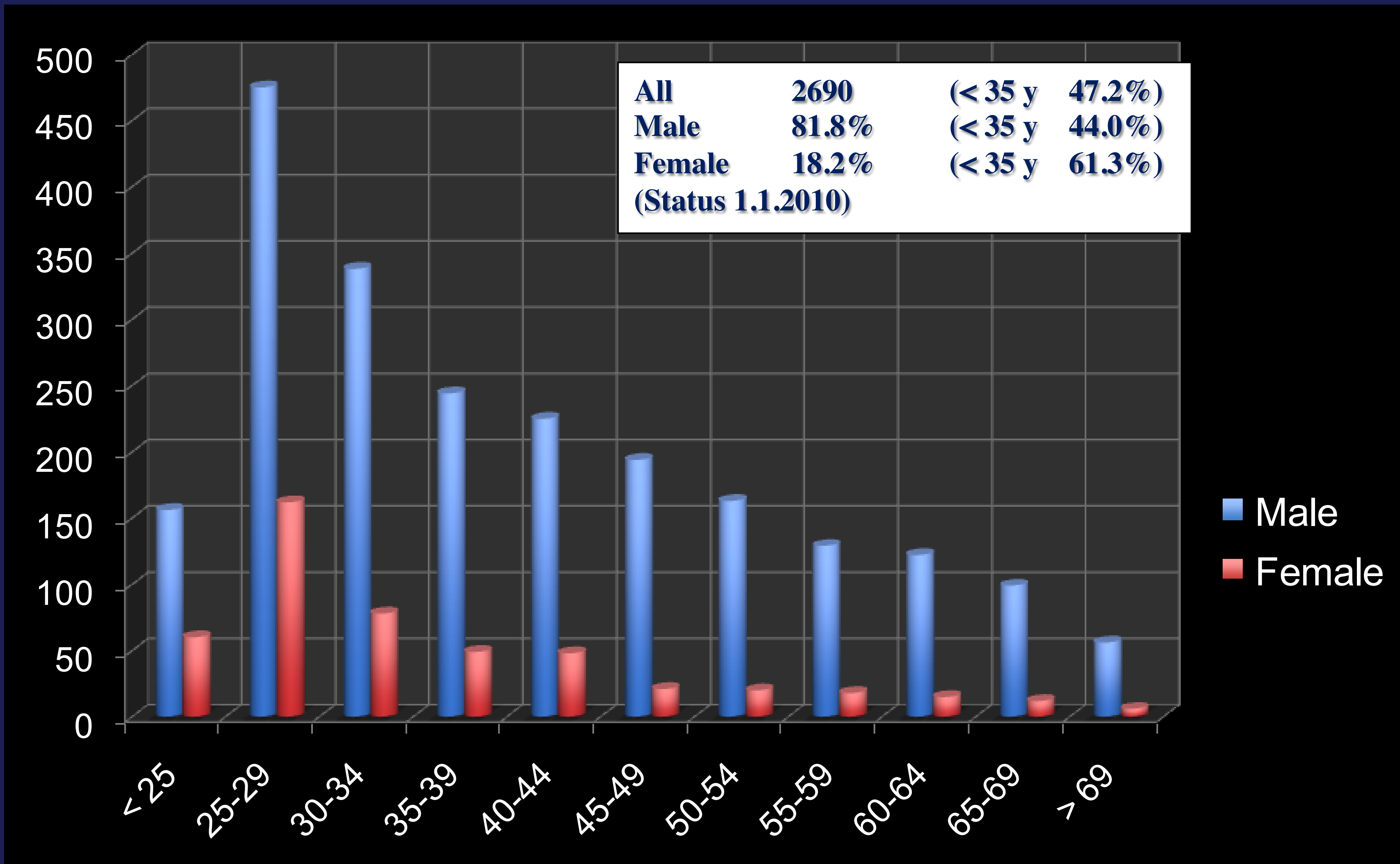
ATLAS Collaboration

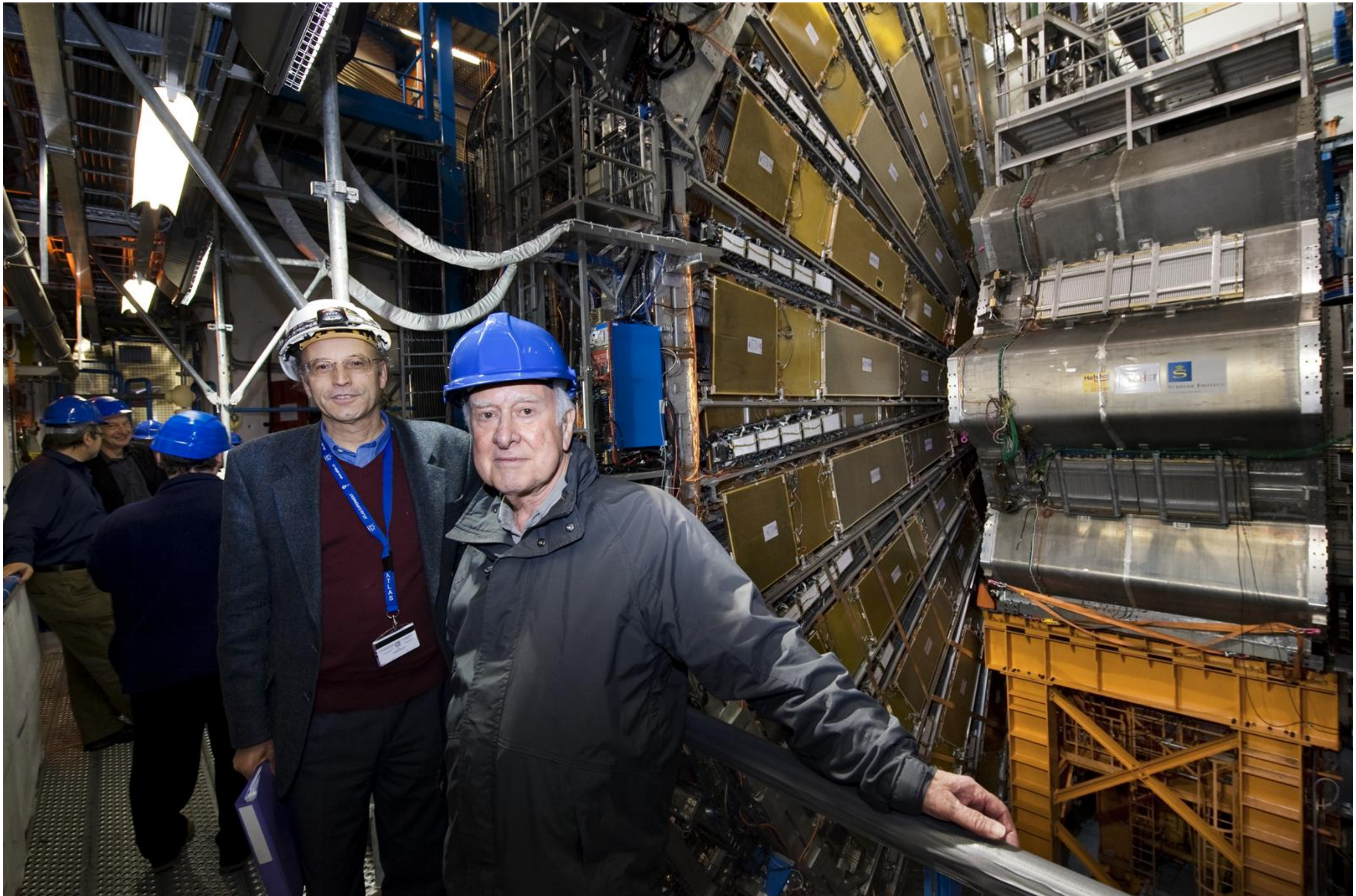
38 Countries
176 Institutions
3000 Scientific participants total
(1000 Students)

founded in 1992

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Brasil Cluster, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, LMU Munich, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, NPI Petersburg, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Warwick, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

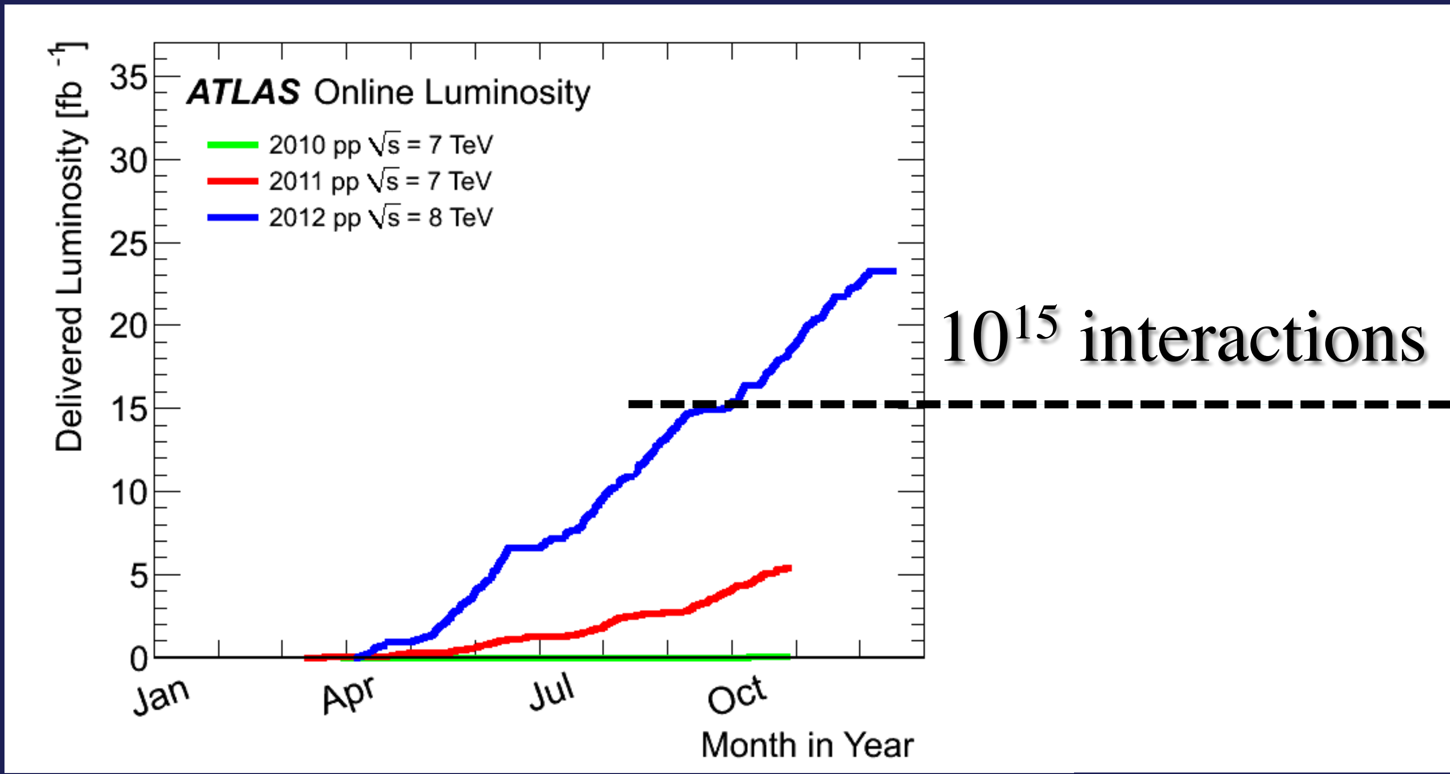
Age and Gender Profile of ATLAS





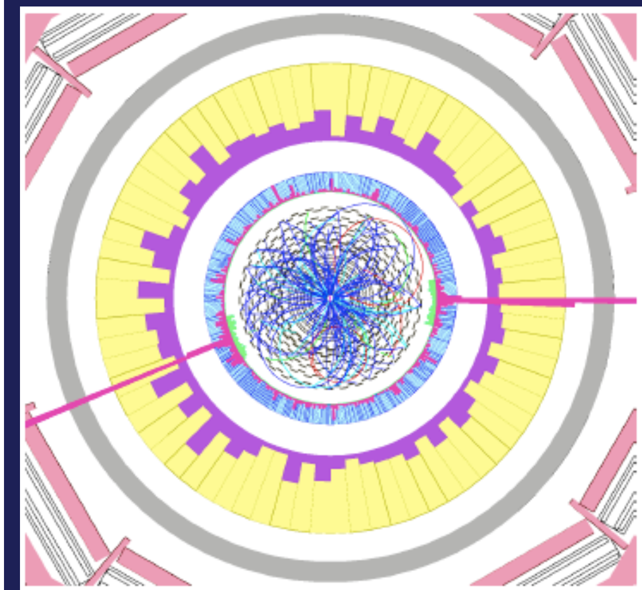
November 23rd, 2009: first pp collision!

LHC Data Taking: 2010-2012

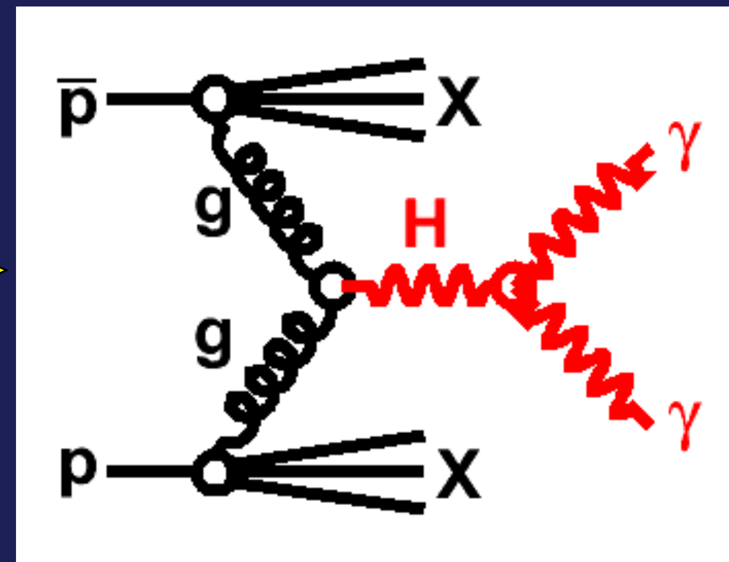


- **24/7 operation typically from March – October each year**
- **Rate of interactions:**
  - **About 1 billion interactions per second**
  - **Fast "trigger" decision => record about 400 events/second**

How to detect the Higgs Boson

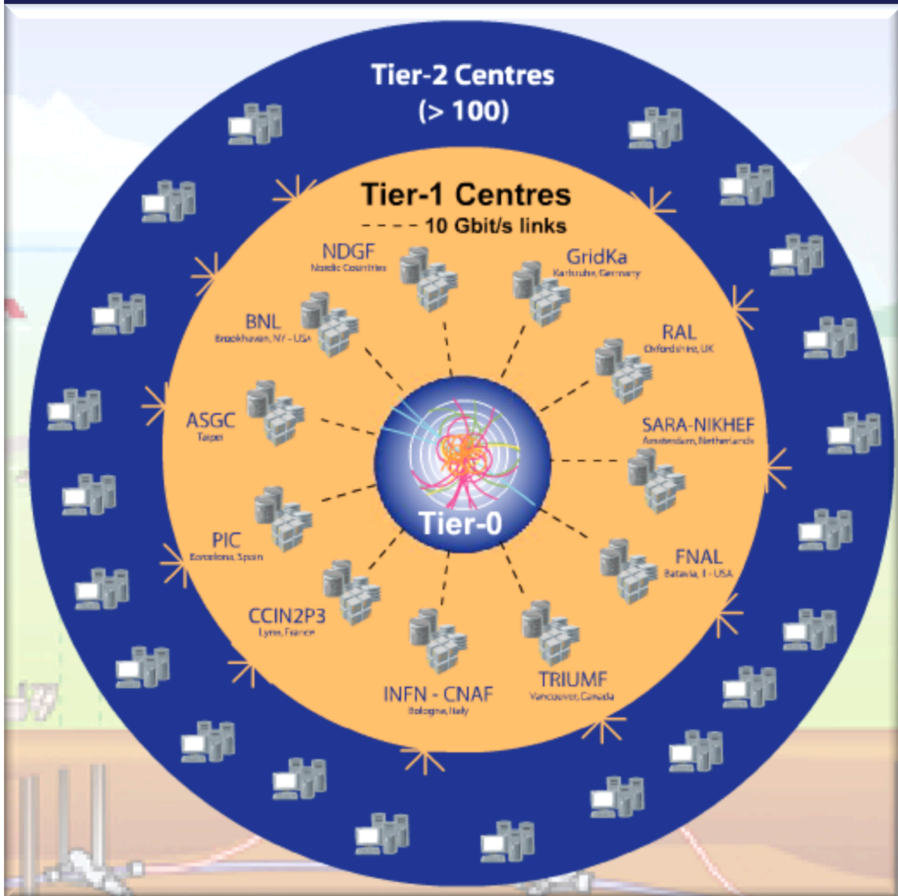


Higgs ?



- Measured hits in large detectors
- => use hits to reconstruct particle paths and energies
- => estimate background processes
- => understand the underlying physics

Worldwide LHC Computing Grid



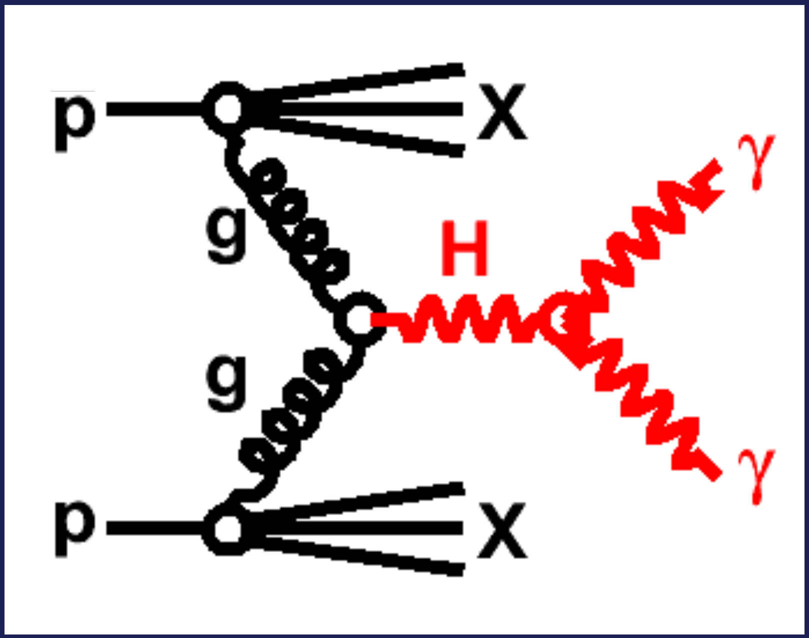
- Huge data volumes
  - 600 MB/s
  - 5,000 TB/year
- Huge CPU requirements:
  - 15 s/event

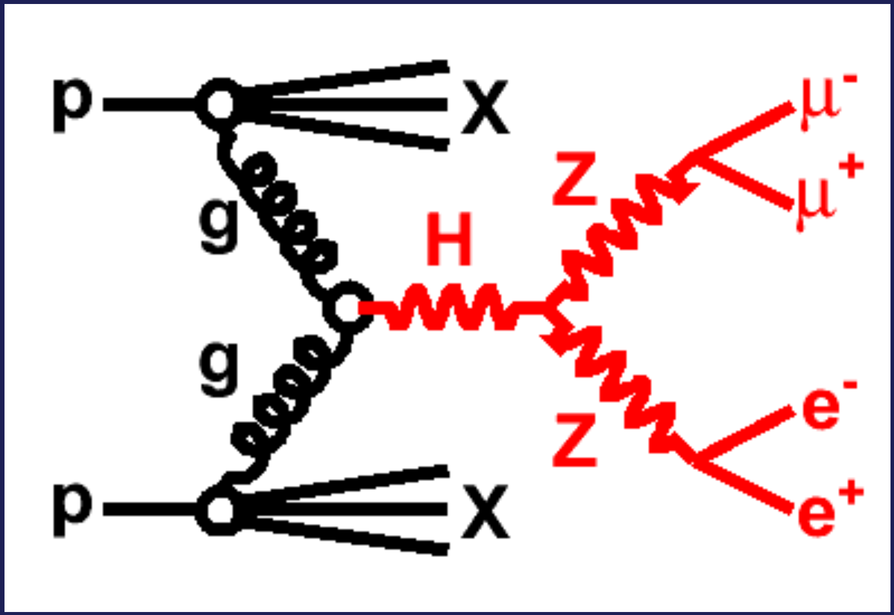
Data stored and analyzed on world-wide LHC computing grid:

11 clouds across the globe

The Higgs Boson Search

Production and Decay of a Higgs Boson

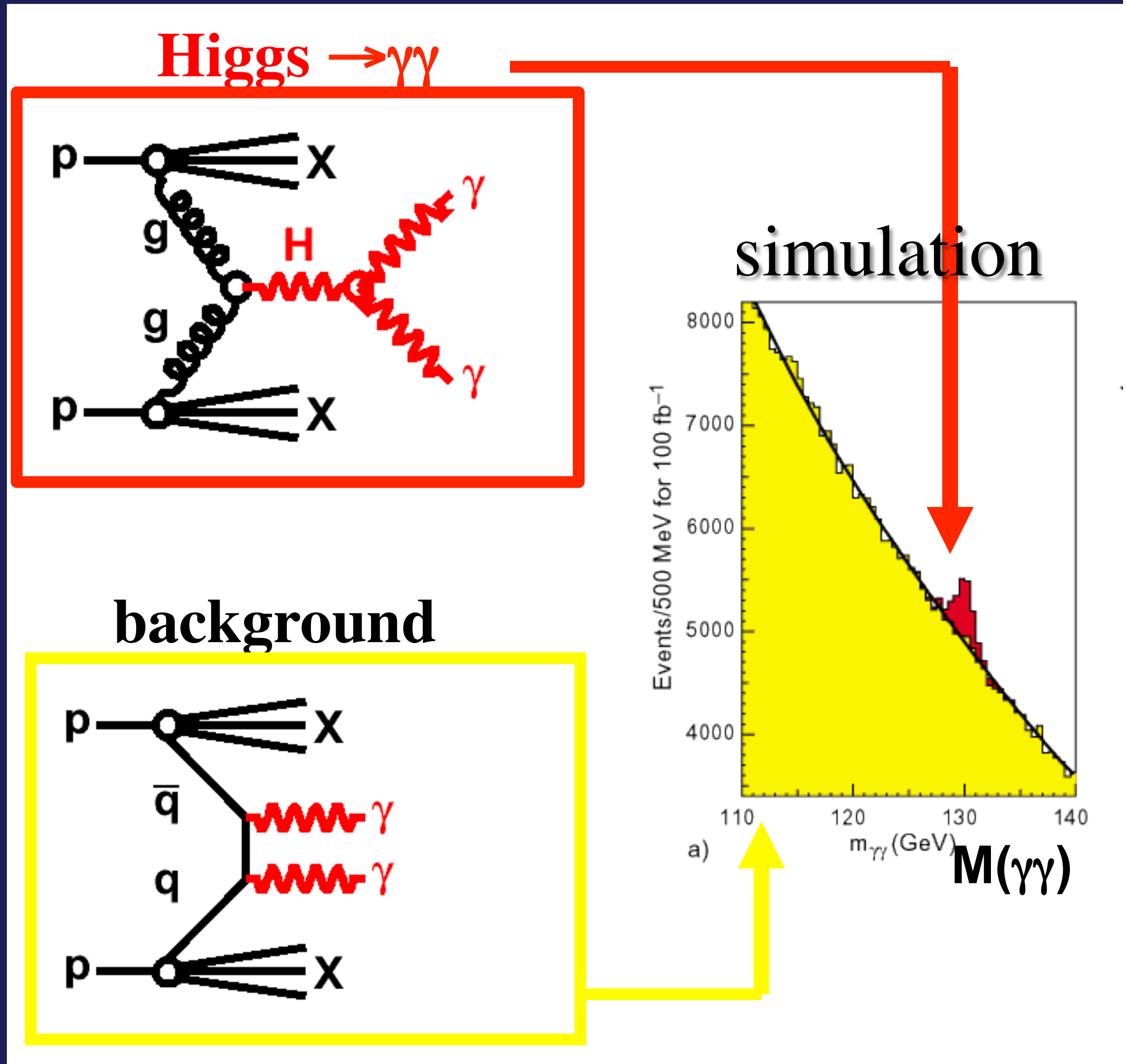




- Higgs boson is unstable and decays very quickly
  - 0.2% decay into **two photons**
  - 0.014% decay to **4 electrons or muons**
  - 99.8% of decays are harder to observe
    - also analyzed and important but will not explain here

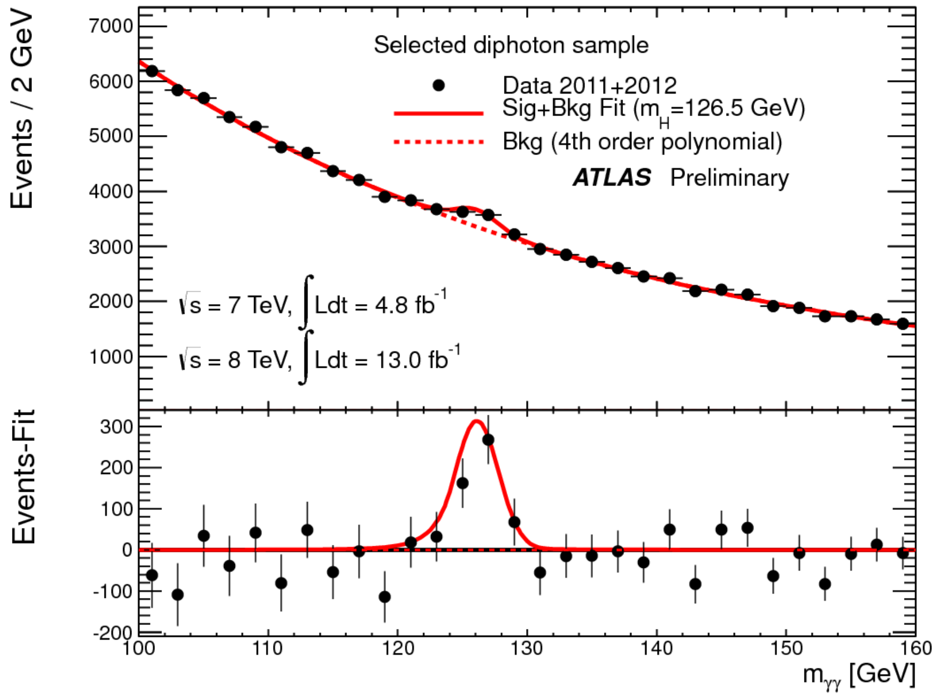
Finding the Higgs Boson (with photons)

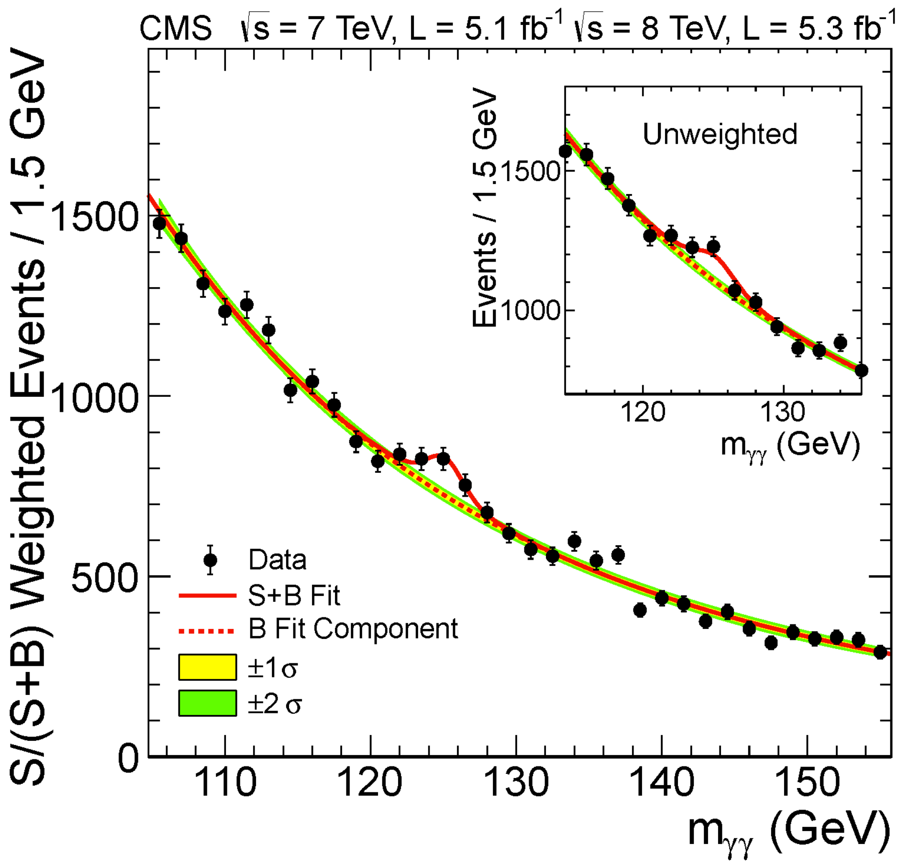
- Higgs boson decays to two high energy photons
  - Higgs mass determined from energies and angles of photons
- Background process looks identical
  - But creates no peak!



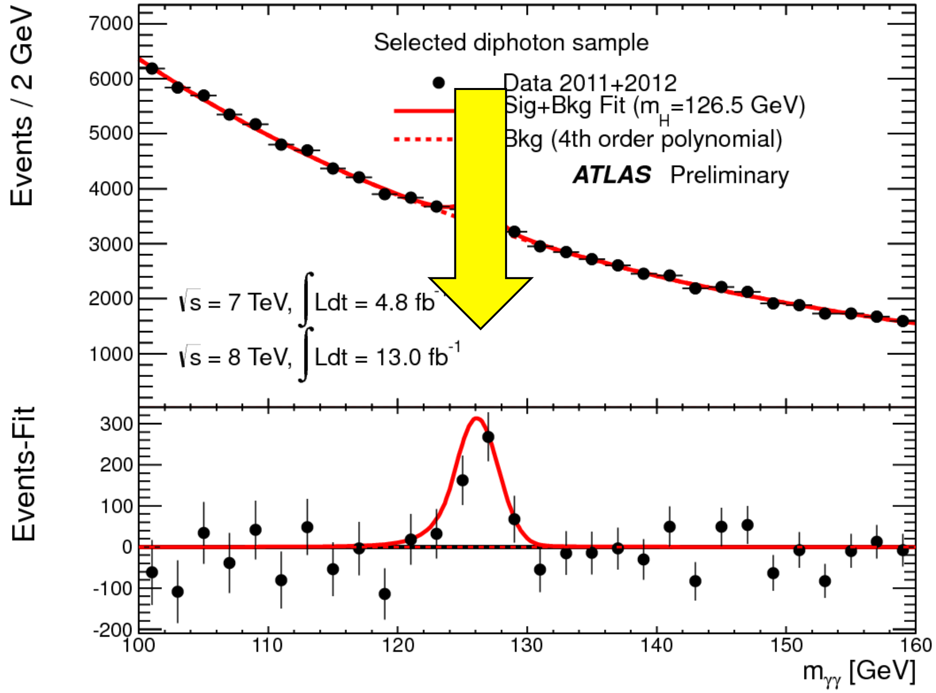
$$M_{Higgs} \approx M(\gamma\gamma) = 2\, E_1\, E_2\, (1\text{-}\cos\alpha)$$

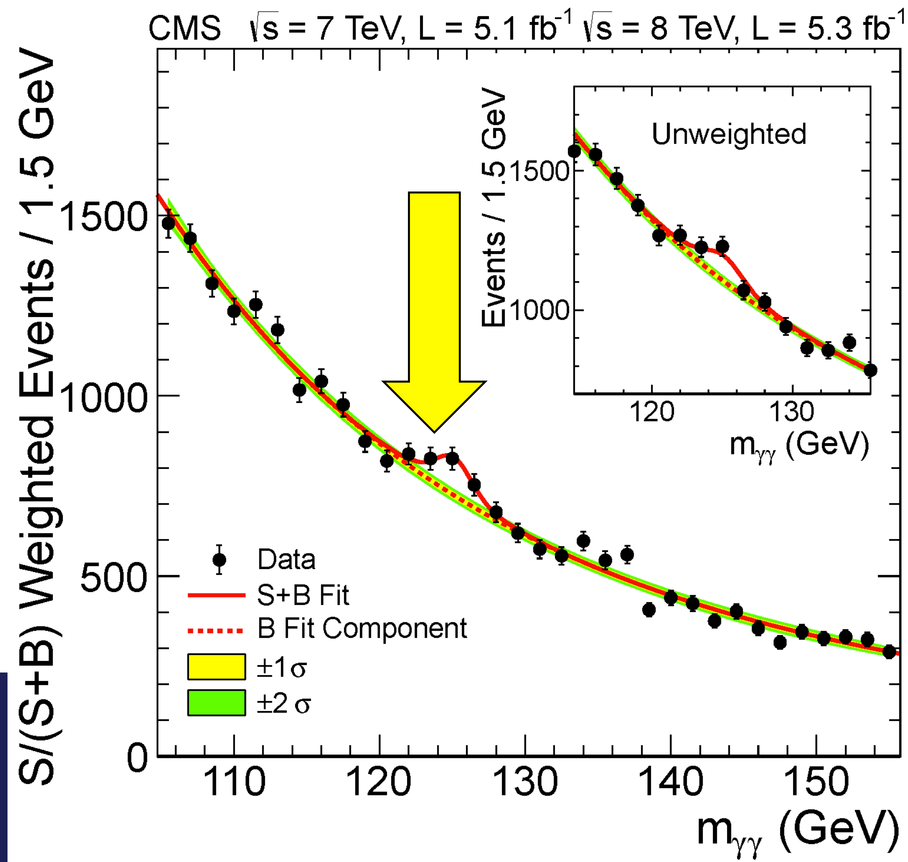
Diphoton Mass Distributions



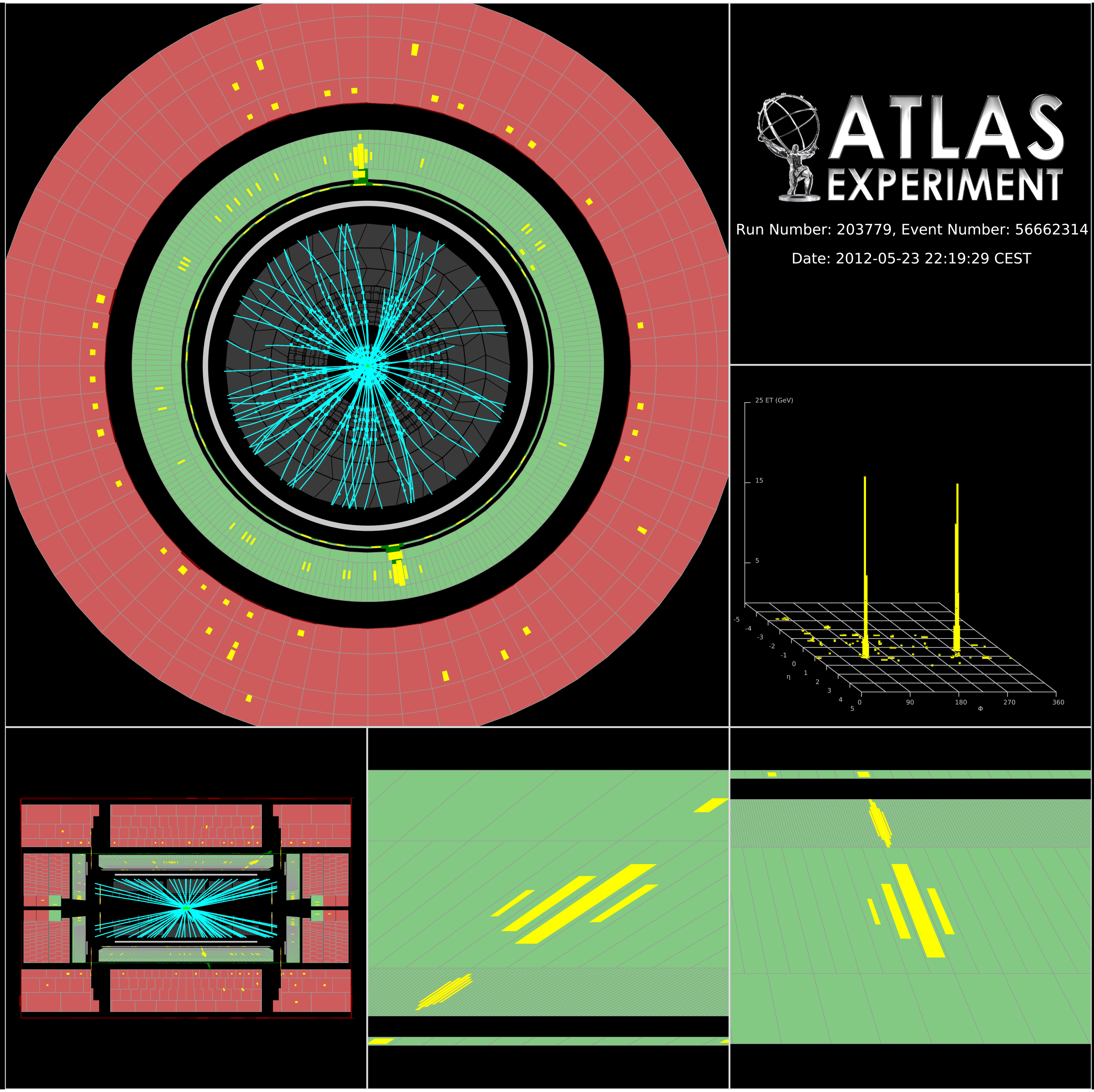


Diphoton Mass Distributions

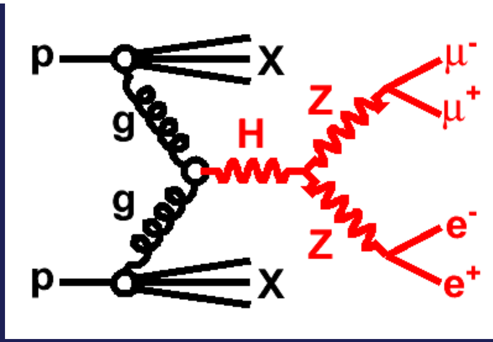


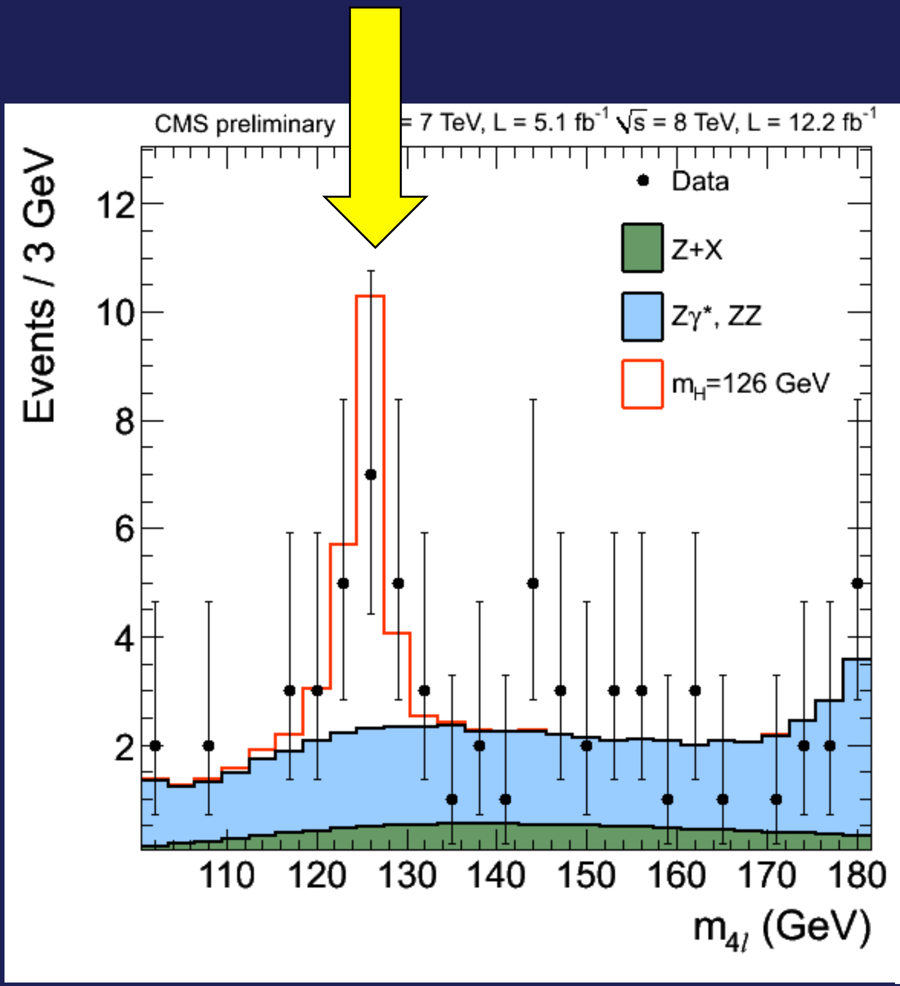


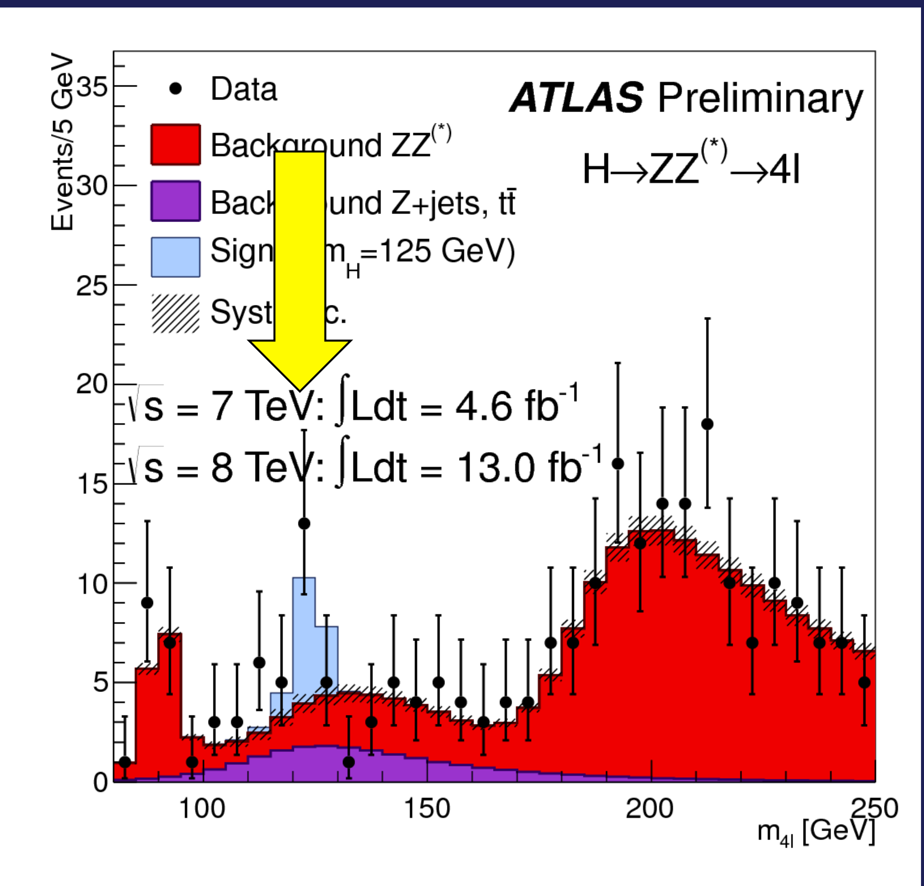
Both experiments see peak at ~126 GeV


ATLAS
EXPERIMENT
Run Number: 203779, Event Number: 56662314
Date: 2012-05-23 22:19:29 CEST
25 ET (GeV)
15
5
η
Φ
0
90
180
270
360

Higgs boson decaying to two Z bosons







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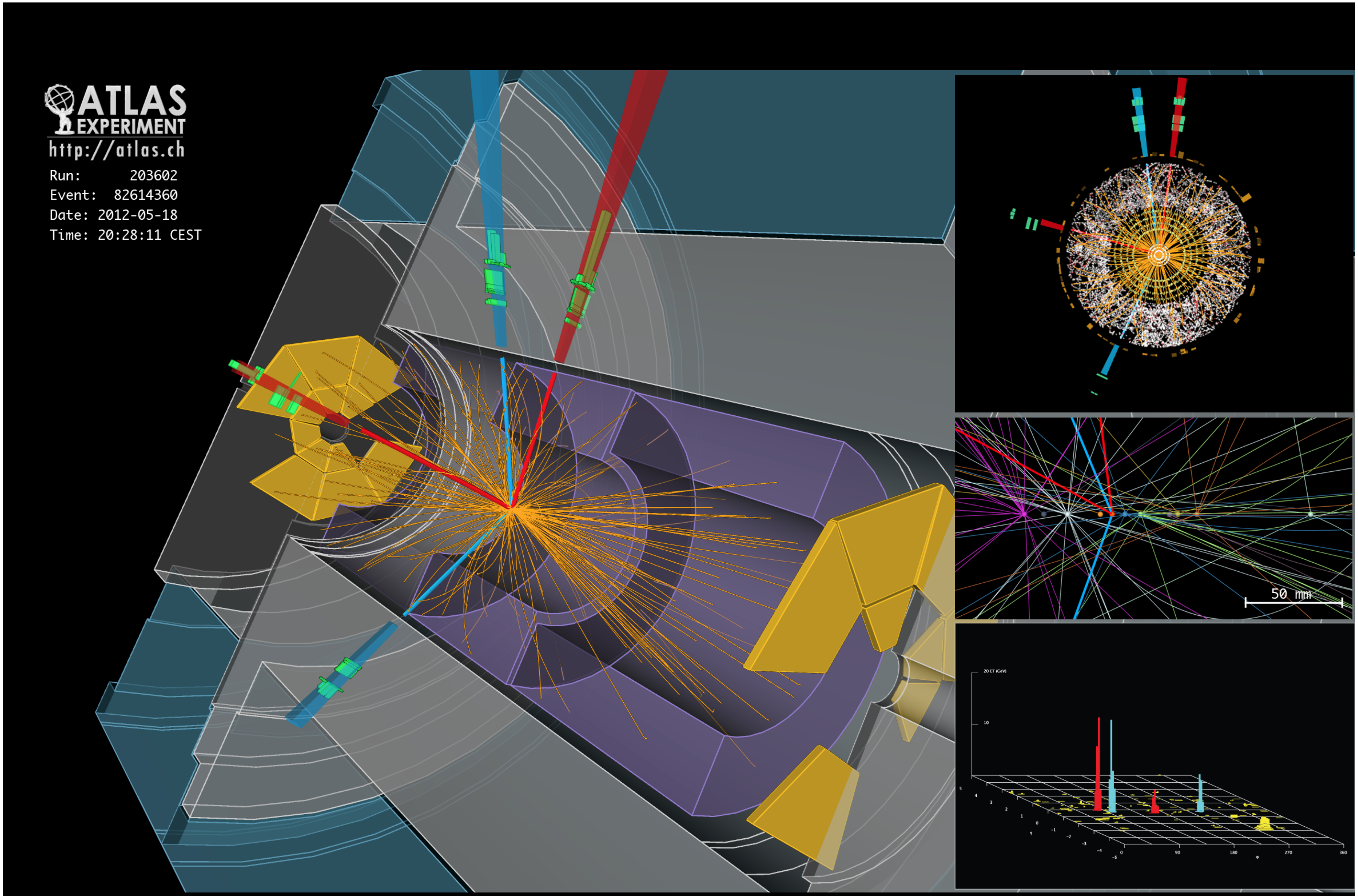
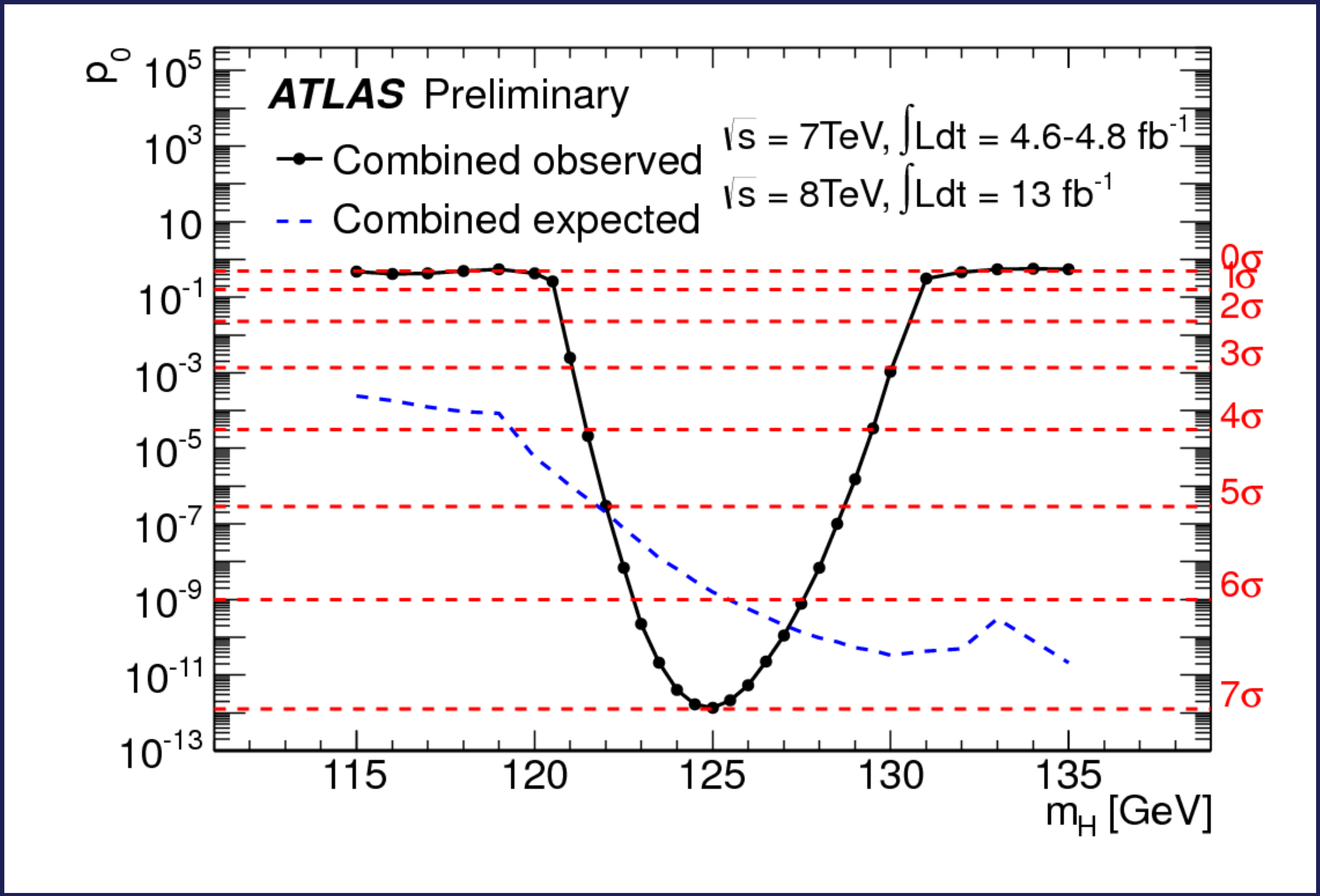

ATLAS
EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST
50 mm

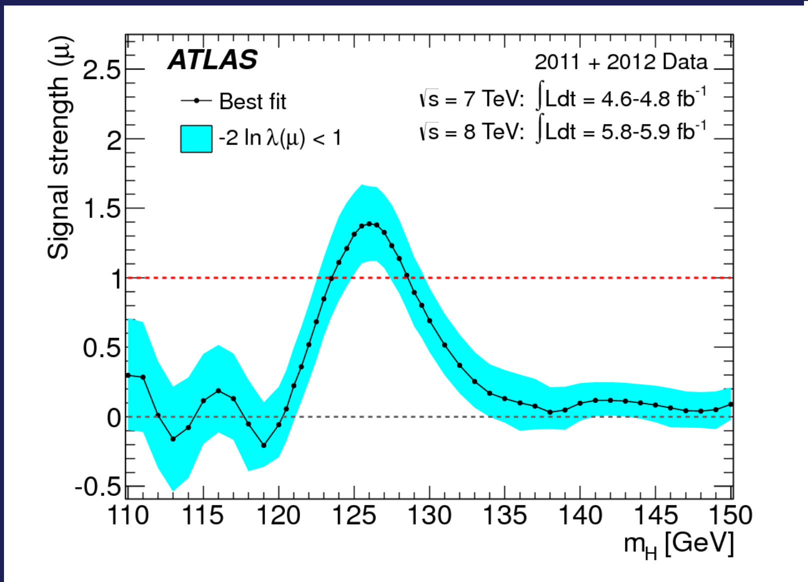
Probability of statistical fluctuation

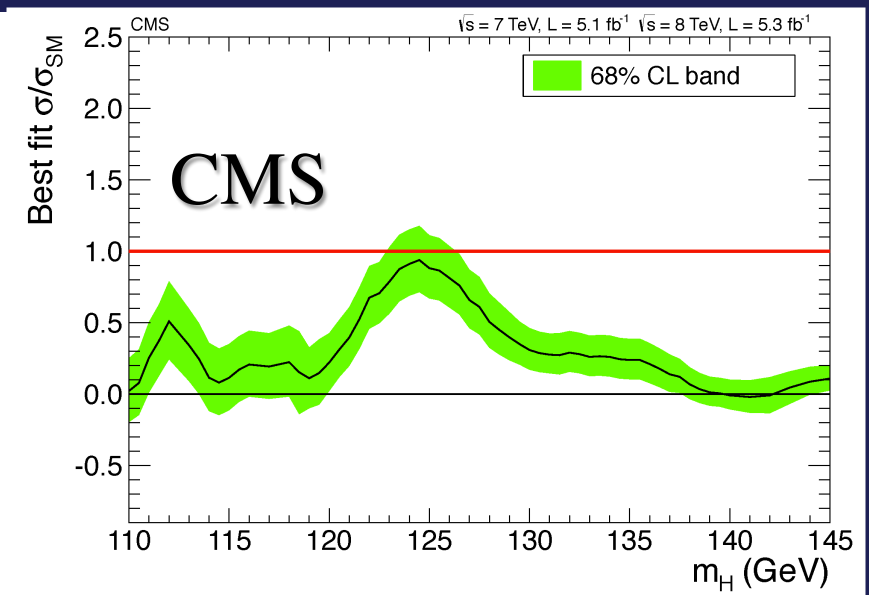


Probability of statistical fluke less than one in 100 billion

Discovery of a New Particle!

- Properties similar to those of Higgs boson
  - Signal strength consistent with expectation





  - Mass consistent between the two experiments:
    - ATLAS: **m=125.2 ± 0.7 GeV**
    - CMS: **m=125.8 ± 0.6 GeV**

Conclusions

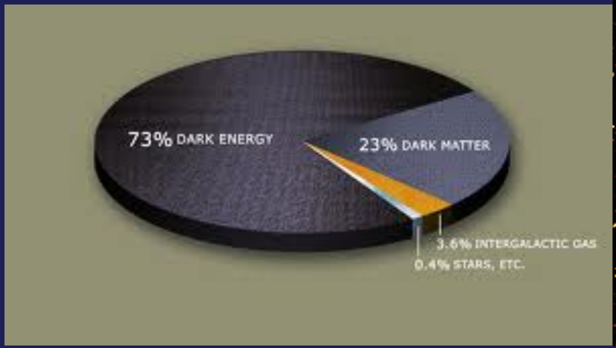
Fabiola Gianotti, ATLAS spokesperson

Peter Higgs

- **1964**: Higgs boson first thought of
  - – explains how fundamental particles get mass
- **1992**: ATLAS and CMS collaborations founded
- **2012**: New particle observed consistent with Higgs boson

Outlook

- Many puzzles remain in Standard Model
  - Many other analyses ongoing in parallel at LHC
    - e.g. searches for Dark Matter particles



- LHC will have a 2-year break to do repairs
- 2015: nearly double the energy (8 => 13 TeV)
  - Great chance to discover other new particles
  - Further study Higgs boson
    - Is it fully consistent with our Standard Model?

Public Lecture, Friday May 3rd, 5pm

Berkeley on Friday, May 3rd 2013 by **Dr. Fabiola Gianotti** from CERN ("European Organisation of Nuclear Research").

Dr. Gianotti was the spokesperson of the ATLAS collaboration from March 2009 until March 2013. The ATLAS experiment is one of the two experiments at the Large Hadron Collider (LHC) in Switzerland that announced the observation of a new "Higgs-like" boson on July 4th 2012. Dr. Gianotti made the presentation of this discovery on behalf of the ATLAS collaboration at at CERN on that day. Aside from the Higgs boson search, the ATLAS experiment is also looking for many other new phenomena, e.g. new particles predicted by **Supersymmetry**, a theory invented by **Bruno Zumino** and his collaborator Julius Wess in 1974 when they both worked at CERN.

Dr. Gianotti received her PhD from University of Milan in 1989, working on searches for Supersymmetry in the UA2 experiment at CERN. Since 1996 she is employed by CERN as a Research Physicist. She has been involved in the ATLAS experiment since the beginning of the project, in 1990, working on detector development, design and construction, becoming Physics Coordinator in 1999, Deputy Spokesperson in 2004 and Spokesperson in March 2009. In the period 1996-2000 she has been involved in the ALEPH experiment at the CERN LEP e+e- Collider, where she has worked on data analysis and coordinated the Supersymmetry group.

In March 2011 she was included by The Guardian newspaper in the "Top 100 most inspirational women". Since June 2012 she is member of the Italian Academy of Sciences ("Accademia dei Lincei"). In September 2012 she was awarded the honor of "Grande Ufficiale" by the Italian President Giorgio Napolitano. In December 2012 she was among the recipients of the Fundamental Physics Prize of the Milner

http://ctp.berkeley.edu/brunofest/PublicLecture.html

More Information

- Information, explanations, movies, images …
  - http://public.web.cern.ch
  - http://atlas.ch
  - http://cmsinfo.cern.ch/outreach